Agricultural vulnerability to tephra fall impacts

A thesis

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by

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Dairy cows with snow-capped Mt. Taranaki in the distance

This thesis is dedicated to my cousin, Carl Dixon.

I repacked my suitcase before every trip.

Abstract

Understanding agricultural impact from tephra hazards and their causal mechanisms is vital when developing mitigation and recovery strategies. It is well documented that tephra can impact agricultural systems. However, forecasting likely impacts has been challenging and focused on creating generalised models where impacts typically increase with tephra thickness or loading. Lack of quantitative data and insufficient sample sizes of impact assessment studies restrict potential analysis. However, previous studies have identified that impacts will be governed by the complex interaction of tephra characteristics (thickness/loading, grain size, leachates), exposed farm characteristics (farm size/type, pre-existing conditions), climate, time of year and existing risk management.

Post-eruption impact assessments (Post-EIA) have been used to retrospectively investigate tephra impacts to agriculture, including exploring how tephra and vulnerability characteristics of exposed farms interact. In this study, Post-EIA are used to investigate impacts to agricultural land from three silicic eruptions (2011 Cordón Caulle, 2008 Chaitén, and 1991 Hudson) in Patagonia. Analysis of 49 impacted farms suggests that the characteristics of tephra fall are important, but that the vulnerability characteristics of the farms have a stronger influence on impact. Findings show appropriate recovery strategies employed by farmers are crucial for reducing losses.

This analysis is used to: 1) develop an improved understanding of the factors that influence agricultural impacts from tephra fall; 2) design standardised impact assessment guidelines and databases; and 3) develop improved tephra fall risk assessment methodologies fragility functions that include different agricultural vulnerabilities due to farm type, intensity, seasonality, and leachable fluoride. These initiatives aim to build predicative capacity and ultimately aid disaster risk reduction strategies.

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Submitted to: Journal of Applied Volcanology (4 June 2015)

The manuscript was prepared and written by Heather Craig. The concept of the paper was designed by Heather Craig based on discussions with Dr. Thomas Wilson and Dr. Carol Stewart. Dr. Wilson and Dr. Stewart contributed to field work and to the refinement of the manuscript. Ms. Valeria Outes, Dr. Gustavo Villarosa and Dr. Peter Baxter assisted in the field, undertook additional interviews and provided review comments of the manuscript.

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Heather Craig wrote the majority of the manuscript (80%), with significant input and refinement by Dr. Carol Stewart. Dr. Thomas Wilson, Dr. Stewart, and Heather Craig developed the concept of the manuscript through discussions. Dr. Stewart, Dr. Sally Gaw, and Dr. Chris Oze aided in the development of laboratory testing methods. Heather Craig undertook the laboratory work and interpreted results. Water samples were taken by Dr. Stewart, Ms. Valeria Outes, and Dr. Gustavo Villarosa. Ash and soil samples were taken by Heather Craig. All authors provided and in depth review and discussion of the manuscript.

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Agricultural impact assessment and management after three widespread tephra falls in Patagonia, South America (Chapter Four)

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Heather Craig designed and wrote the majority of the manuscript (90%), with input and refinement by Dr. Thomas Wilson. Dr. Carol Stewart offered insightful discussion and review. Dr. Wilson and Dr. Stewart undertook fieldwork in the Chaitén area and this manuscript used their field data. Similarly, Hudson data was taken from Dr. Wilson's field notes. Cordón Caulle field-work was completed by Heather Craig, Dr. Wilson, Dr. Stewart, Dr. Gustavo Villarosa, and Ms. Valeria Outes. All authors contributed to the refinement of the manuscript. Dr. Shane Cronin provided input to early design and later review of the manuscript.

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Impacts of the June 2011 Puyehue-Cordón Caulle volcanic complex eruption on urban infrastructure, agriculture and public health (Appendix D)

Submitted as: GNS Science Report 2012/20

Heather Craig was third author on the report and contributed to field data collection, writing sections of the report, and provided reviews. Dr. Thomas Wilson and Dr. Carol Stewart were lead authors on the report and wrote the majority of the report. Other co-authors (Dr. Peter Baxer, Ms. Valeria Outes, Dr. Gustavo Villarosa, and Dr. Elizabeth Rovere) contributed to field data collection, writing and reviewing of the report.

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Chapter One

Introduction

Explosive volcanic eruptions are one of the most powerful geophysical phenomena on Earth. These eruptions can produce a spectrum of volcanic hazards, the most frequent and widespread being tephra fall (Wilson et al. 2012). Tephra can be dispersed hundreds of kilometres from the vent and cover vast areas, depending on the wind direction and magnitude of the eruption. The resulting disruption and damage can impact large numbers of people, infrastructure and primary industries.

Agriculture is a vital primary industry that relies on stable, productive environmental systems. Agricultural systems are often concentrated in volcanic areas as tephra deposits weather to fertile soil in the long term (Shoji et al. 1993). This increased fertility means that these areas are often settled and intensively farmed. The resident population and associated agricultural systems are exposed to tephra hazards, if the volcanism remains active (Tilling 2005). The world’s expanding population is increasingly reliant on agriculture for food security. There is a growing need for enhanced understanding of the effects that tephra has on agricultural systems.

Previous studies have investigated the effects that tephra has on agricultural systems and their recovery after the events. These studies have mostly focussed on the impacts to soil, vegetation and animal health. Broadly grouped, the most significant impacts to agriculture are those caused by the physical nature of the tephra. These impacts include coverage, loading and smothering of vegetation, and changes to the soil's physical properties. Physical tephra impacts to livestock, including eye and tooth abrasion, excessive tephra ingestion leading to blockage of the rumen and starvation from feed destruction (Antos & Zobel 1985; Cook et al. 1981; Mercado et al. 1996; Rees 1993; Smith & Staskawicz 1977; Thorarinsson 1979; Wilson et al. 2011a).

The severity and longevity of impacts can also be increased by continued remobilisation of tephra, especially in arid to semi-arid and high precipitation, tropical environments

(Wilson et al. 2011b). Events where agricultural losses can be attributed to chemical effects of tephra are less frequent, but livestock deaths are known to occur due to fluorosis following ingestion of tephra (Cronin et al. 1998; Cronin et al. 2003; Georgsson & Petursson 1972; Johnston et al. 2000). Widespread reporting of the instances where tephra fall has had toxic effects on livestock, pasture and water supplies, has led to common misconceptions around the importance of the chemical impacts of tephra (Wilson 2009). The vast majority of case studies suggest that for severe chemical impacts unique volcanological, agricultural and climatic conditions are required. Most case studies indicate tephra falls of <20mm will provide beneficial macro- and micro-nutrients to soils and plants (Ayris & Delmelle 2012). However, due to exceptions to this trend and the need to address agriculturalist's concerns, robust chemical assessment methods are needed.

The most common remediation method is the cultivation of the tephra into the soil A-horizon allowing for rapid assimilation and weathering of the tephra into the soil matrix. It also prevents remobilisation of tephra and encourages aeration and bioturbation, further enhancing tephra incorporation (Neild et al. 1998). Direct seeding of the deposit has also been suggested, but this is problematic as it is most effective when the tephra layer is very thin and is strongly dependent on the fertility characteristics of the specific deposit in question (Wilson 2009).

Impacts and appropriate recovery recommendations can be very different due to the physical and chemical properties of the tephra, the climate, the existing farming systems and the mitigation actions taken (Wilson et al. 2014). The way in which these impacts and variables are assessed and mitigated against can also vary between different governments and social groups. This leads to a diverse range of impacts that are very difficult to predict or model. Extensive data has only been gathered on events that have occurred in the last 30 years (Wilson et al. 2012). As there are no guidelines for collection or recording of impact assessment information, only a limited number of case studies have been studied in sufficient detail for true quantitative comparisons to be drawn (Jenkins et al. 2014). There is a need for a more holistic, integrated approach that can be applied to multiple events in different volcanological and agricultural settings.

Due to the high exposure of agricultural systems to tephra and associated impacts, accurate predictive models in order to forecast and minimise impacts are needed. Ideally, this predictive capacity needs to be developed to integrate different vulnerability characteristics as well as various tephra fall properties and intensities. Currently, vulnerability assessments have produced functions that describe agricultural production losses for various farm types (pastoral, horticultural, forestry, etc.) at various tephra thicknesses (Wilson & Kaye 2007). However, these do not take into account numerous other factors that contribute to a farm's vulnerability such as, farm size, access to machinery/irrigation, feed supplies, pre-existing condition, as well as climate, time of year, and risk management strategies in place. This narrows the applicability of the functions and further refinement is needed to ensure accuracy in numerous, complex scenarios. When vulnerability assessments are combined with probabilistic hazard models (models that show the probability of a certain hazard intensity occurring, e.g., for tephra fall the probability or return period of a certain tephra thickness occurring), a risk assessment can be undertaken. This allows for the probability of a certain set of impacts occurring to be calculated. Risk assessments are powerful tools as they allow for impacts to be anticipated which means that preparedness planning and disaster risk reduction (DRR) strategies can be put in place. The promotion of DRR and building of resilience is a major focus of the United Nations International Strategy for Disaster Reduction, outlined in the Sendai Framework (UNISDR 2015). Therefore, the understanding and quantification of risk is vital as the targeted DRR strategies, which risk assessments inform, will result in less severe impacts due to natural hazards such as tephra fall.

Gaining an initial understanding of the impacts to agriculture after a tephra fall event is also important, as these post-event impact assessments (post-EIA) are vital in providing information to emergency managers to coordinate and plan response post-event, to identify areas that may need evacuating, and help aid distribution planning (Alexander, 2002). Increased understanding of agricultural impacts and the specific hazard and vulnerability factors causing them, will also allow mitigation strategies to be targeted to address specific issues. Employing more mitigation schemes that target specific impact mechanisms (e.g., fertilisation of soil and tephra based on the fertility measures of each, or stabilisation techniques targeted to specific tephra grain sizes) successfully minimises the severity of impacts (Wilson et al. 2011b).

This chapter presents an overview of the physical and chemical impacts that tephra fall can have on the different components of an agricultural system (soil, vegetation, and animal health). Additionally, the tools that can be used to better assess the likely impacts to agricultural systems are also reviewed. This includes risk assessments, where the probability of both the hazards characteristics and its impacts are assessed, using a hazard model and vulnerability assessment information (ISDR 2009). This chapter concludes with a summary of the thesis objectives and structure.

1.1 Tephra fall

Tephra is a significant hazard from volcanic eruptions. Its effects can be much more widespread than other hazards such as lava flows, lahars, and pyroclastic flows. As a result tephra can impact a greater population causing disruption to communities and their infrastructure (Blong 1984).

Tephra is a corrosive material with a high surface area, originating from the fragmentation of magmas and volcanic rocks and therefore is a primary volcaniclastic deposit. Tephra includes volcanic ash material less than 2 mm in diameter, and larger fragmented material such as lapilli (White & Houghton 2006). The impacts that tephra will have on the environment are dependent on the physical and chemical parameters under which it is formed, as this determines the material's characteristics (Dingwell et al. 2011).

Tephra is formed by a number of physical processes. Within the magma chamber, bubbles begin to nucleate when magma becomes super saturated in volatiles. When the energy within the chamber is high enough to offset the energy needed to maintain a gas-liquid boundary bubbles can form. Within a homogenous magma the energy requirement is higher than in a heterogeneous mix where nucleation can occur around impurities. In a silicic magma, the bubble densities are usually around 10^{14} – 10^{16} per

m^3. Bubble growth is limited initially just by the magma viscosity, then slows as diffusion of water cannot keep up. This results in magma ascent, during which some of the volatiles are lost. Instabilities in the fluid develop as the magma ascends and becomes decompressed creating a fragmentation wave that causes brittle fracturing. The degree of fragmentation determines the texture and size of the resultant clasts. In silicic tephra, fine tephra shards are formed by rupture of small bubble walls by a decompression wave, which correlates with eruption intensity (Cashman et al. 2000).

The chemical characteristics of the tephra grains are determined by the chemistry of the magma that formed them, whereas soluble surface chemistry is comprised of volatiles that are scavenged in the volcanic plume. This surface chemistry commonly includes acidic salts, and other volatile metallic elements, with fluoride (F^-), chloride (Cl^-), sulphate (SO_4^{2-}), calcium (Ca^{2+}), and sodium (Na^+) the most commonly occurring (Witham et al. 2005).

1.2 Impacts of tephra fall on agriculture

Tephra fall affects agricultural systems due to its impacts on interdependent critical infrastructure (Fig. 1.1), animal health, vegetation condition, and soil fertility (Fig. 1.2).

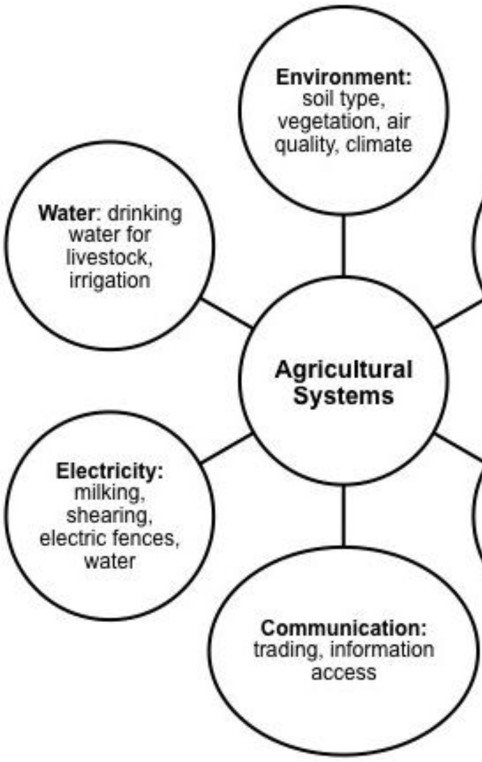

Figure 1.1: Diagram showing the systems that affect agriculture. Disruption to these systems will lead to increased agricultural losses.

1.2.1 Agricultural systems and interdependencies

Agricultural impact assessment studies both before and after tephra fall events have been undertaken (Table 1.1). These studies have focussed on the identification of impacts, and also the factors that influenced the specific impacts. These factors can be grouped into hazard intensity metrics (HIM) and vulnerability characteristics (VC). HIM are the characteristics of the hazard that measure its severity, for tephra fall these include deposit thickness (mm), loading (kg/m^2), and leachable and total element concentrations. VC are properties of the affected agricultural systems that influence the relative vulnerability (or resilience) to tephra fall events. These are not related to the tephra hazard so can be recorded prior to an event, however VC are often more difficult to quantify than HIM due to the qualitative nature of some aspects. VC of agricultural systems include: farm type, farm size, soil properties, access to farm 'improvement' assets such as cultivation and irrigation machinery, the climatic conditions at the affected farm, and the season/stage in animal/crop growth that the tephra fall occurs in. Impacts from a range of events and the HIM and VC thought to influence these outcomes are shown in Table 1.1.

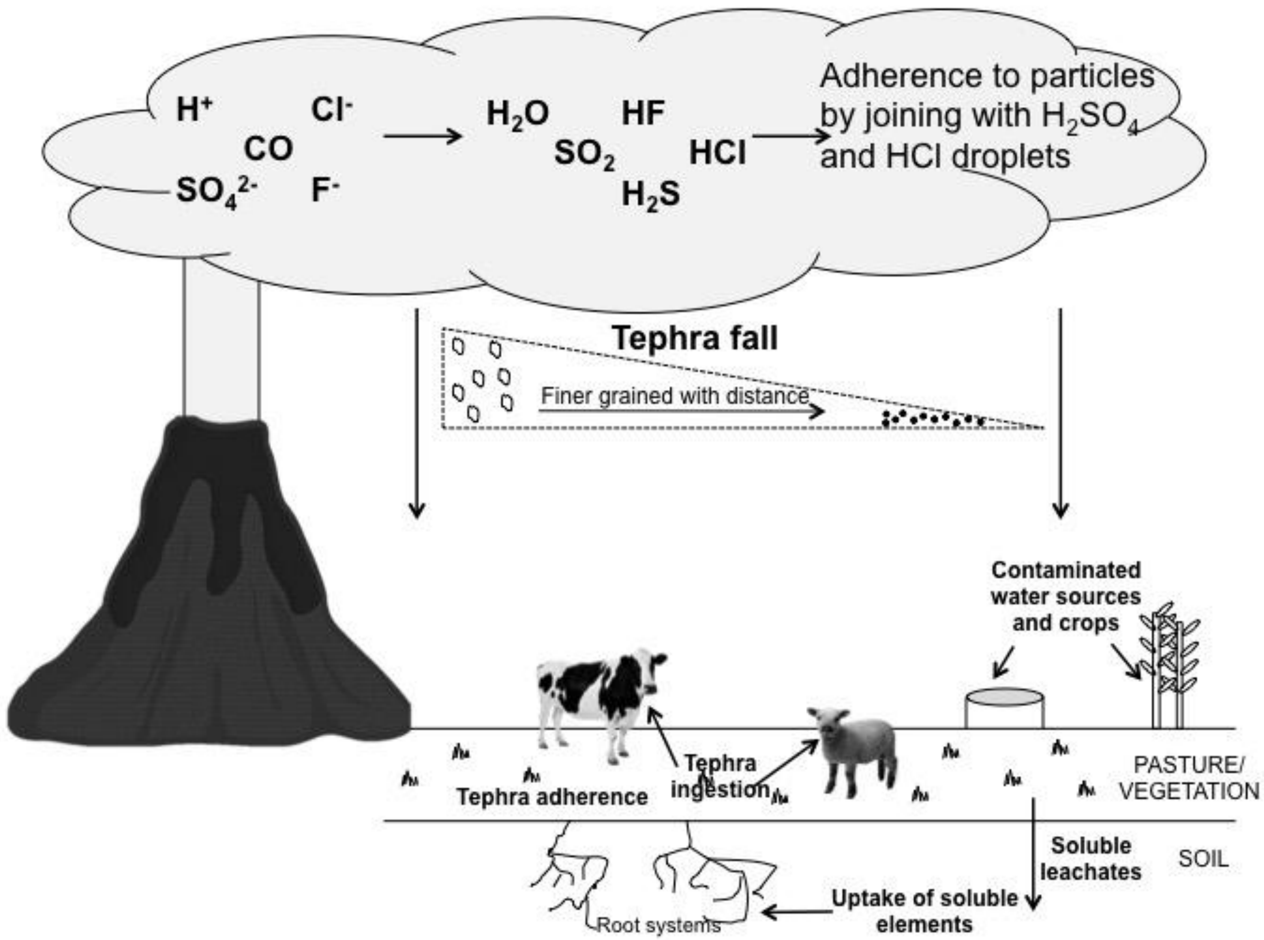

Figure 1.2: Tephra fall deposition and impacts on agricultural systems, including animals, vegetation and soil.

Agricultural systems cannot efficiently operate without reliance on external infrastructures. These systems are also vulnerable when exposed to tephra fall. Tephra fall can cause electricity outages due to tephra accumulating on lines and insulators causing flashover, and abrasion to switches (Wardman et al. 2012); road closures due to loss of vehicular traction and low visibility (Wilson et al. 2014); building damage due to tephra loading on structures (Jenkins et al. 2014); and disruption to water supplies due to contamination of water sources and filtration systems, and abrasion of pumps (Stewart et al. 2006). These effects all have a cascading impact on agricultural systems that usually use this infrastructure (Fig. 1.1).

1.2.2 Physical impacts

Most previous studies (Table 1.1) have established an overall trend of increasing severity of impacts to agricultural systems with an increase in tephra thickness and/or loading. Some of these works explore the impacts in greater depth revealing that both the characteristics of the tephra (HIM) and the characteristics of the exposed agricultural system (VC) can both have sometimes considerable influence on the level of tephra fall impact. For instance the importance of tephra thickness as a HIM that influences impacts is well established with the relationship between increased tephra thickness and more severe impacts has been identified after numerous events (Blong 1984). Access to farm 'improvement' assets such as irrigation and cultivation machinery and shelter for livestock, are an example of a VC that has been observed to influence impacts after numerous events, notably after the 1991 Hudson (Chilé) eruption (Wilson et al. 2011). As tephra fall increases to very large thicknesses (>300 mm) the influence VC or any HIM other than thickness/loading falls away and severe impacts are quite uniform (Blong 1984; Cook et al. 1981; Neild et al. 1998).

Within the 0-300 mm band, the grain size of the deposit is an important physical characteristic, especially when considering the potential for wind and/or fluvial remobilisation of the tephra deposit. Many of the physical impacts to soil and vegetation can be linked and to some extent forecasted by the physical properties of the tephra deposit.

Table 1.1: Major case studies documenting the impacts and influences on agricultural losses after tephra fall, in descending year of eruption date.

Volcano	Year	Local agriculture	Physical Impacts	Chemical Impacts	Losses	Influencial HIM identified	Influential VC identified	Refer-ence
Kelud, Indonesia	2014	Rice, tobacco, tomatoes, corn, pineapples, cloves, coffee; some cows, sheep, goats, chickens mostly for domestic consumption.	Serious crop damage due to loading to most vegetation within a 15km radius of the vent, abrasion to coffee crops, breakage of clove trees within 5km of vent. Rice paddies required re-irrigating	Some acid burns on vulnerable crops such as tomato plant leaves	Crop losses of up to Rp 377 billion (US$28 million). Fruit yield down by up to 30%. Many crops abandoned and replanted in the most proximal 10 km.	Tephra fall was not toxic, increased thicknesses the major indicator of losses.	Rice crop resilient to ashfall. Low intensity livestock farming in feedlots decreased animal vulnerability. Farmers were used to tephra fall and knew to cultivate it in or reseed where necessary. Strong community education programme. Rainfall 10 days after the eruption prevented wind remobilisation and rinsed crops but did cause some lahars.	Blake et al. *in review*
Merapi, Indonesia	2006	Rice, tobacco, corn, maize, corn, tomatoes; some cows, sheep, goats, chickens mostly for domestic consumption.	Crops smothered by ashfalls, particularly those >35mm. Tobacco, tomatoes, peppers and corn were vulnerable to stems snapping at >30mm depth.	Acid burns on plants even when ash thickness as low as 2mm. Chemical impacts on livestock not established (no autopsies).	Chilli pepper, tobacco, tomatoes and corn losses up to 80-100%. Losses lower for crops such as potatoes, onions and cabbages (up to 30%). Cattle weight loss due to contamination of feed lead to their prices dropping by up to 75%. Autopsies were not undertaken.	Some issues with tephra acidity, losses primarily due to thickness/loading.	Rice crop resilient to ashfall. Low intensity livestock farming in feedlots decreased animal vulnerability. Farmers were used to tephra fall and knew to cultivate it in where necessary.	Wilson et al. 2007

Volcano	Year	Local agriculture	Physical Impacts	Chemical Impacts	Losses	Influencial HIM identified	Influential VC identified	Refer-ence
Tungurahua, Ecuador	1999-2009	Maize, beans, potatoes, citrus fruits, bananas; chickens and cattle for dairying.	Tooth abrasion, starvation and stomach blockages in cattle. Issues with hot ash burning crops in proximal areas.	Chemical burns to foliage caused plant deaths. Citrus trees burnt in 1999 still small and unhealthy in 2004. 6-8 years soil fertility recovery predicted.	Livestock sold off at less than half price, causing some bank closures. High calf mortality rate. In areas with >200mm ash 100% of crops died.	Chemical burns caused horticultural losses. Abrasiveness of tephra caused teeth wear in grazing animals. Thickness determining pasture availability.	Rainfall after some eruption sequences led to better incorportion into soil compared to others. Access to machinery for cultivation and supplimentary feed decreased losses.	Leonard et al. 2005
Mt. Ruapehu, New Zealand	1995-1996	Mostly sheep and cattle for dairying, some horticulture.	Tooth abrasion in cattle. Some vegetation breaking due to tephra loading.	30-1500 kg/ha of sulphur added to >25,000 km^2 of land. Soluble (in water) fluoride levels were around 24-28 mg/kg of tephra.	2000 sheep died 80km NE of the vent (2.5% of sheep in the area) and 3 dairy cows also died, due to suspected fluorosis. These deaths were likely caused by a combination of fluorosis and their existing poor condition. Some sulphur accumulation (in brassica) approached toxic levels.	Thickness determining pasture availability. Fluoride concentrations in tephra causing suspected fluorosis in animals in sub-optimal condition.	Animal condition at the time contributed to losses (pregnant animals died). Access to machinery for cultivation and supplimentary feed decreased losses.	Cronin et al. 1998; 1997; 2003; Johnston et al. 2000

Volcano	Year	Local agriculture	Physical Impacts	Chemical Impacts	Losses	Influencial HIM identified	Influential VC identified	Refer-ence
Hudson, Chile	1991	Livestock farming for meat and wool, some horticulture in irrigated areas.	Up to 2000mm of tephra fall. Stomach blockages causing injury and eye irritation in animals. Tephra accumulating in fleeces until sheep could no longer stand up. Remobilisation of ash caused continued problems.	Some reports of acid damage to fruit tree leaves. Lack of pre-eruption data did not allow for quantifying soil chemistry changes. Showed some evidence of limited fertilisation of sulphur.	Approximately 1 million sheep and thousands of cows died due to tephra covering feed. Farm abandonments occurred in the Ibanez Valley (800-2000 mm ash) and the steppe region (up to 75mm ash).	Thickness/loading determining pasture availability. Grain size contributing to remobilisation.	Climate controls wind remobilisation potential, with semi-arid farms sustaining much higher losses than temperate zone farms. Access to feed, machinery and ability to evacuate also influenced losses.	Inbar et al. 1995; Wilson et al. 2009; 2011a; 2011b; 2012
Pinatubo, Phillipines	1991	Rice, vegetables, sheep, cattle and poultry farming.	Up to 30 cm of tephra was deposited on the flanks of the volcano that was used for rice and vegetable farming. Crops were smothered. Farmers' houses and shed roofs were collapsed by the weight of the wet ash causing human and animal casualties.	Intense rainfall at the time meant that the tephra was quickly leached. No chemical issues were reported.	96,200 ha of agricultural land covered by ashfall causing US$36.2 million in agricultural damage (including lahars and remobilised tephra).	Tephra loading destroyed buildings and crops. No chemical issues reported.	Rainfall in some areas prevented wind remobilisation but caused damaging lahars. Access to suplementary feed, and the resilience of farm buildings to tephra loading also contributed.	Mercado et al. 1996

Volcano	Year	Local agriculture	Physical Impacts	Chemical Impacts	Losses	Influencial HIM identified	Influential VC identified	Reference
Mt. St. Helens, USA	1980	Fruit trees, hay, potatoes, cereals, legumes.	Issues with photosynthesis in crops where leaves covered with ash. Plant breakages due to loading common. No issues with stomach blockages in livestock. Acted as mulch in some places, lead to good wheat crop.	Salt damage on fruit tree leaves. No toxicity issues in plants or animals observed. Small amount of sulphur added to soil.	US$15 million lost in apple production due to slowed growth. Favourable growth conditions after the eruption means that some crop losses may be masked.	Thickness/loading smothered some pasture and crops. Tephra coated plants and prevented photosynthesis. Some chemical damage to fruit trees and pulse of sulphur added to soil.	Rainfall in some areas rinsed crops and accelerated tephra weathering into soil. Access to equipment and water to rinse horticultural crops, especially fruit trees. Seasonality meant that most crops were mature enough to withstand some tephra loading.	Antos & Zobel 1985; Cook et al. 1981; Dahlgren Ugolini, & Casey 1999; Dale et al. 2005; Lyons 1986
Hekla, Iceland	1970	Mostly sheep farming with some crops.	Up to 200mm of tephra deposited proximal to vent. Chemical issues were more important due to small amount of ash needed to cause lethal fluorosis.	Only 1mm of tephra was shown to cause fluoride toxicity and deaths in sheep. Grass contained 4300ppm fluoride. This dropped rapidly in the weeks after the eruption.	Thousands of sheep deaths due to acute fluorosis. Contamination of feed meant that large amounts had to be discarded as even small amounts of ash caused animal health issues.	Tephra leachates contained toxic levels of fluoride leading to widespread fluorosis in animals. Thickness determining pasture availability.	Access to shelter and supplementary feed stocks were the biggest influence on animal mortality. Ability to cultivate tephra into soil also influenced outcomes.	Thorarinsson & Sigvaldason 1971

Volcano	Year	Local agriculture	Physical Impacts	Chemical Impacts	Losses	Influencial HIM identified	Influential VC identified	Reference
Paricutin, Mexico	1943-1956	Cattle, horses and some sheep and goats. Small amount of food crops.	All plant life within a 5km radius of the cone died due to smothering by 150-200mm of tephra. Animals showed some respiratory stress.	Deposits that were able to be cultivated into the topsoil provided some fertilisation.	Area within 10km of vent mostly abandoned after manual tephra removal proved too difficult. Cultivation of deposit into soil successful at <150mm thickness. Approximately 4000 animals died.	Cone formation and tephra thicknesses smothered vegetation.	Access to machinery to remove or cultivate in tephra deposit.	Eggler, 1963; Rees, 1993

1.2.2.1 Physical impacts on soil

Physical impacts of tephra on soil, that can have a negative effect on agricultural systems, include loss of permeability, cementation and temperature changes.

The permeability of the tephra dictates the extent that water and gas can be exchanged by the underlying soils. This exchange is influenced by the grain size and pore spaces in the tephra deposit. Coarser tephra allows for high infiltration rates that are greater than the underlying soil. Smaller tephra particles can block pore spaces and drainage channels, decreasing the infiltration of water (Diaz et al. 2005).

Cementation of the tephra deposit can further reduce infiltration and environmental interaction. Cementation often occurs after moderate rainfall, the exact mechanisms are not fully understood but it is likely that this effect is more common in fine grain sized deposits (Cook et al. 1981; Dale et al. 2005). This increases surface runoff that prevents erosion of the deposit and can also increase erosion of uncemented adjacent areas (Collins & Dunne 1986).

Silicic tephra albedo (up to 0.8) is often much higher than the existing soil (usually 0.1-0.4) (Ayris & Delmelle 2012). This difference means that more radiation is reflected which can cause a decrease in temperature. Conversely, some darker coloured, more mafic tephra can have a lower albedo than soil, increasing soil temperature, causing heat stress in root structures in the soil, and cell damage (Smith et al. 2010). The high albedo of silicic tephra was shown to reduce temperature by up to 10°C after Mt. St. Helens (Cook et al.1981).

One positive physical impact of tephra deposition on soils is the mulching effect, when a layer of tephra covering the soil acts as a mulch and prevents evapotranspiration of water, whilst still allowing water infiltration. This is particularly beneficial in areas where rainfall levels are low and has even been suggested to be useful as a commercial application (Tejedor et al. 2003). The benefits of this impact have been seen at various sites such as Mt. St. Helens and Hawaii’s Haleakala Crater (Cook et al. 1981; Pérez

2009). This demonstrates that tephra deposition does not always have consistently negative effects, and in some cases can aid agricultural systems. However, it is important that the tephra thickness and/or loading is not high enough to negate the positive influence of the mulching effect by completely smothering the soil. The exact thickness that the positive effect of mulching becomes negated is not well defined, and likely differs significantly based on complex environmental factors and specific tephra properties.

1.2.2.2 Physical impacts on vegetation

A visible negative impact of tephra deposition on vegetation is the burial of the plant structure. Plant deaths were observed at Mt. St. Helens and Hudson due to smothering and tephra burial, structural breakages, and the prevention of photosynthesis and normal gas exchange (Cook et al. 1981; Wilson et al. 2011a). This is typical of the physical damage that tephra fall inflicts on vegetation and is highly dependent on the deposit thickness and loading at a given site, and the vulnerability of the affected vegetation. For example, pastoral death and limited recovery likely occurs when tephra deposits exceed 100 mm (Wilson 2009), whereas for fruit tree orchids death will not occur until much greater tephra fall depths.

Overloading of the plant structure can also cause the plant to compensate for the increased downward pressure and physiologically change. This is highly dependent on the growth stage of the plant, with immature plants being much more susceptible. More prostrate plants may have less physical damage but may also be buried easier. Surface tephra may also cause root structure growth to alter and move deeper to avoid the affected soil (McLaren & Cameron 1996). The most commonly observed physiological change is stunted plant growth (Ayris & Delmelle 2012), which was observed at Tungurahua and Merapi (Sword-Daniels et al. 2011; Wilson et al. 2007). In the weeks and months following the tephra fall, desiccation cracks in tephra deposits provide pathways for re-emergent vegetation which allows for some growth through thick tephra deposits (Antos & Zobel 1985).

Tephra coverage can also inhibit photosynthesis, hampering vegetation growth and regeneration, as tephra particles in the air reflect sunlight and cover leaf surfaces (Hobbs et al. 1981). Coverage of leaves blocks light and also impedes gas exchange. This coverage will be dependent on the grain size (a fine grain size is needed to adhere to leaves) and the thickness (which will determine the amount of coverage) of the tephra deposit. The usual response is for stem growth to accelerate (Smith et al. 2010), however when under pressure from the tephra fall this is not possible. Tephra can also be highly abrasive to plant leaves especially when wind remobilises the deposits. This was an issue at Mt. St. Helens where some plant die off occurred due to plant tissue abrasion (Cook et al. 1981).

1.2.2.3 Physical impacts to animal health

Grazing animals such as cattle, sheep and goats are a large part of agricultural systems. These animals are highly exposed to tephra when grazing and can easily ingest large amounts even in thin tephra deposits (Edwards et al. 2004), causing digestive issues. The most common being rumen blockages that lead to starvation or internal injuries. This was observed at Hudson where the tephra formed a hard block in ruminant's stomachs which caused intestinal swelling to push against the lungs leading to asphyxiation (Wilson et al. 2011a). At Mt. St. Helens, whilst no major blockages were reported, experiments showed that it took 5 days for ingested tephra to pass through cattle's systems (Sneva et al. 1982).

Feed and water sources covered by tephra can become unpalatable to animals. Water requirements in livestock also increase after tephra fall due to the hygroscopic effect of tephra, placing further pressure on agricultural water supplies (Wilson et al. 2009). If supplementary feed and water is not brought in, animal deaths from starvation and dehydration can occur.

Tephra can wear down the teeth of ruminants during grazing of contaminated feed. This can severely impair their grazing ability eventually leading to starvation. It can also be costly to farmers as in effect the animals are prematurely aging. Abrasion of teeth was seen in dairy cows in Ecuador after both the Reventador and Tungurahua eruptions

(Leonard et al. 2005; Sword-Daniels et al. 2011). This issue was also identified after the Hudson and Ruapehu eruptions (Neild et al. 1998; Wilson et al. 2011a).

1.2.3 Chemical impacts

Whilst the majority of case studies have shown that the physical effects are the most severe and cause the greatest amount of agricultural losses, chemical impacts can also be significant in some areas. Chemical effects are also of concern to farmers and associated stakeholders. Therefore it is vital to provide chemical information and incorporate this into the tephra analysis protocol.

1.2.3.1 Impacts to soil

pH

Acidic material scavenged in the plume is released as leachates attached to tephra, into the environment and causes the pH of the underlying soil to decrease. This pulse is usually short lived and can be diluted or buffered by the soil (Ugolini & Dahlgren 2002). Soil acidity can cause the oxidation of sulphur and metallic ions that potentially can lead to continued soil acidity. Continued acidity causes aluminium to accumulate to potentially toxic levels, leading to reduced plant growth (Zheng 2010). It can also cause the loss of essential nutrients such as calcium, potassium and magnesium (Ayris & Delmelle 2011) and a decrease in soil microbial activity (Uexkull & Mutert 1995). As with the physical impacts there is a complex interaction between the effects and the depositional environment. At Kasatochi Island, Alaska and Mt. St. Helens, the pH was much higher in areas with greater rainfall (Dahlgren et al. 1999; Sneva et al. 1982; Wang et al. 2010).

Cation Exchange Capacity (CEC) and primary nutrients

The cation exchange capacity (CEC) and the amount of primary macronutrients (nitrogen, phosphorous and potassium) are the basic measures of fertility of a growing medium (McLaren & Cameron 1996). The CEC of tephra is much lower than that of soil, restricting its ability to exchange nutrients. Often in tephra the total base capacity (TBC) exceeds the CEC, meaning that the cations available exceed the exchange sites available (Wang et al. 2010).

Tephra does not contain organic carbon or nitrogen. These elements play a role in photosynthesis and plant growth (Smith et al. 2010). Concentrations of phosphorous and potassium vary between tephra. Some tephra has very low levels especially if acidic, as this causes the loss of macronutrients (New South Wales Agriculture 1999). Beneficial concentrations of potassium due to tephra leachates have been recorded at Fuego and El Chichón post-eruption, however both found little addition of the other primary nutrients (Varekamp et al. 1984; Veneklaas 1990).

Other elements

Often tephra fall can add beneficial amounts of nutrients to soils. This is especially relevant in areas where soil fertility prior to the eruption was low. Unfortunately, for most elements the amount contained in tephra is so low that in order to gain significant benefits the amount of tephra required would be prohibitive to growth (Ayris & Delmelle 2012). However, there are exceptions to this rule, particularly for sulphur. Sulphur was deposited in useful amounts after the Ruapehu eruption (Cronin et al. 1998). Whilst the addition of sulphur can often be positive there is also a chance that high levels can slow microbial rates and alter the carbon cycle, reducing decomposition (McLaren & Cameron 1996). This was observed at Mt. St. Helen (Dale et al. 2005).
The positive addition of magnesium, calcium and sodium is also often seen due to tephra leachates (Ayris & Delmelle 2012; Cook et al. 1981; Cronin et al. 1998; Neild et al. 1998), however this is generally short-lived and lasts only a few months depending on the environment (Dahlgren et al. 1999).

The element that causes most issues with toxicity after an eruption is commonly fluorine. This is not only due to its abundance in some tephra, but also its tendency to be held within the soil, rather than rapidly leach out like many other elements (Ugolini & Dahlgren 2002). Whilst there is usually no observed impact to soils, there are issues when fluoride accumulates in plants (discussed in section 1.2.3.3). The process of plant uptake of fluoride from soils is not fully understood but is thought to be facilitated by aluminium (Ayris & Delmelle 2012).

Another element, which commonly causes concern amongst agriculturalists, is the heavy metal arsenic. Arsenic can be added to the soil due to the release of tephra leachates, and from there can easily accumulate in vegetation (Gislason et al. 2011). As it is a well documented neurotoxin and carcinogen it is commonly tested for in soil after tephra fall (Baxter et al. 1986).

1.2.3.2 Impacts to vegetation

Chemical impacts to vegetation often manifest themselves as reduced vegetative growth, however this relationship is complex with many mechanisms to consider (Kabata-Pendias 2001). In addition to issues transferred from the growing medium, there can also be surface impacts to existing vegetation.

<u>Chemical burns</u>

Chemical burns to foliage can occur after tephra deposition, due to the acidic nature of tephra deposits. These burns are caused by halide salts, such as chloride and possibly fluoride, and are aided by moderate precipitation after deposition (Ayris & Delmelle 2012; Wilson 2009). Chemical burns can also cause loss of nutrients as the leaf surface is broken and a reduction in photosynthesis as burnt areas become inactive (Smith et al. 2010). Minor plant burns were seen at Ruapehu, Mt. St. Helens and Hudson (Cook et al. 1981; Neild et al. 1998; Wilson et al. 2011a). A controlling factor is the leaf type and morphology. Certain plant species are more vulnerable to chemical burns than others. Particles are much more likely to adhere to hairy leaves rather than smooth flat species (Smith & Staskawicz 1977).

<u>Element uptake</u>

The addition or removal of elements to the soil due to tephra deposits will have a flow on effect to vegetation growing in the medium. This relationship is complex as both the soil and vegetation have some buffering capacity (Kabata-Pendias 2001). However, in general any deficiencies or toxicity in the soil will impact plant health. Heightened aluminium can have serious effects on plant root apex’s and their ability to take up nutrients (Zheng 2010). As increased acidity oxidises and mobilises metallic compounds cell damage can occur (Uexkull & Mutert 1995), however this is very rarely induced by tephra fall.

1.2.3.3 Fluorosis in animals

Accumulation of fluoride in and on vegetation is a serious hazard to agricultural productivity, due to its severe impact on the health of grazing animals. Fluoride present in tephra can be released over a relatively long period of time. Single laboratory leachates have shown to underestimate the long term release of the element (Cronin et al. 2003). As a result many previous studies may have misjudged the importance of F as a tephra contaminant. Fluoride is believed to be the cause of many of the animal deaths from the Laki eruption of the late 1700s that killed 50% of Iceland's livestock (Gislason et al. 2011; Thorarinsson 1969). Fluorosis in ruminants can manifest in many different ways. Symptoms include dental lesions due to the suppression of ameloblasts (enamel forming cells) with skeletal abnormalities such as porous bone shaft growths and calcification of tendons (Suttle 2010). Cattle suffering from fluorosis were identified around Lonquimay in 1989, around 10 weeks after the eruption. Symptoms before death included vomiting, weight loss and bone pain (Araya et al. 1990). After the Ruapehu eruption of 1995, 2000 sheep deaths (2.5% of the animals in the area) occurred due to fluorosis (Johnston et al. 2000). This has led to an increased perception of the risk of fluoride and other toxins from tephra. This is possibly slightly exaggerated, as the deaths may not have occurred if the animals were not in such a poor condition pre-eruption (Cronin et al. 2003). Despite this, fluoride levels and fluorosis risk remain of major importance when assessing the characteristics of a tephra deposit.

1.2.4 Site specific tephra impacts

The climate of an area can dictate both the time taken for tephra to weather to soil and the seriousness of the impacts faced (Shoji et al. 1993). The severity of the impacts described are all partially governed by the length of time that the soil or vegetation comes into contact with the tephra (Ayris & Delmelle 2012). If there is high rainfall that washes the tephra off leaf and plant structure then the chemical and physical impacts may be reduced. This was seen at Merapi after the 2006 eruption, when there was a marked increase in chemical burns to crops that were covered for weeks, compared to those covered for only a few days before being rain washed (Wilson et al. 2007). However, if the rainfall is only moderate then the tephra may cement and form a persistent crust over vegetation and soil, as seen in the months after Mt. St. Helens (Seymour et al. 1983). The Tungurahua eruptions in Ecuador in 1999 and 2001 demonstrate the difference that precipitation after a tephra fall event can have on the impacts faced. The 1999 eruption occurred during a dry period and the plume height rose to 10km. Whilst this increased the risk to aviation, it dispersed the tephra over a greater region which meant that it had a much less severe impact on the proximal farming region. In contrast, the 2001 eruption occurred in a rainy season and the plume reached a much lower altitude. This meant that the intensively farmed proximal slopes of Tungurahua received much greater thickness tephra fall (Le Pennec et al. 2012). These case studies show that rainfall can be both increase and decrease the severity of impacts faced, again highlighting the complexity of environmental interactions and tephra impacts.

Wind removal of tephra can also be beneficial as it reduces tephra residence time, however this can also have negative effects as the material can be continually remobilised throughout the region, exacerbating and lengthening the impacts. This was seen in Hudson after the 1991 eruption, where ‘ash storms’ were observed throughout the 1990s (Wilson et al. 2011b). This means that there is a delicate balance between environmental factors reducing the residence time, and causing negative effects such as continued remobilisation by wind and cementation with precipitation. This again further complicates the hazard prediction model and long term recovery forecasting, but needs to be taken into account.

Whilst in general the greater the thickness and/or loading of the tephra deposit, the more severe the impacts, however when considering a specific event there are additional considerations which complicate this relationship. As research moves towards more accurately understanding and forecasting impacts, a more holistic approach that takes into account different HIM, VC, and the environmental characteristics of the exposed area (such as climate and remobilisation potential) is needed (Wilson et al. 2012). The quantification of the influence that the different VC of exposed areas have on agricultural impacts is a major knowledge gap, which is slowing the creation of more robust risk assessment models and the targeted DRR strategies that these risk assessments inform.

1.3 Risk and impact assessments

Impact and risk assessments are vital to disaster risk research as they provide:

- Tools to predict the likely consequences from an event, which allows for preparedness planning.
- Quantification of impact severity, which can allow for cost/benefit analysis of pre-event mitigation such as land-use planning and the purchase of resilience building assets (i.e., shelter, feed stores, machinery); and post-event mitigation measures such as evacuations.
- Information on the distribution and severity of impacts once they have occurred so that response and mitigation strategies can be tailored for a particular set of impacts to minimise the negative consequences. (Blaikie et al. 1994).

Impact and risk assessments both aim to quantify and predict the consequences of a hazard event, by relating hazard, exposure, and vulnerability characteristics (Fig. 1.3; Smith, 2013). Risk assessments are undertaken using a probabilistic approach, where rather than showing a single set of likely impacts, a range of impact scenarios are presented with probabilities attached to each (Wilson et al. 2014). Impact assessments do not rely on a fully probabilistic hazard model, therefore do not have true probabilities of the likelihood of outcomes occurring. Both types of assessments can be undertaken both before and after a hazardous event, and rely on a vulnerability assessment being undertaken to fully forecast or understand impacts. Vulnerability assessments account for how the specific characteristics of a system influence impacts that will occur under different hazard intensities (Fuchs et al. 2012). Currently, research on quantifying the vulnerability of assets (both infrastructure and agriculture) to tephra fall is less advanced than the understanding of the probability of a given HIM for most areas (Wilson et al. 2014). This research gap needs addressing in order to continue to refine impact and risk assessments.

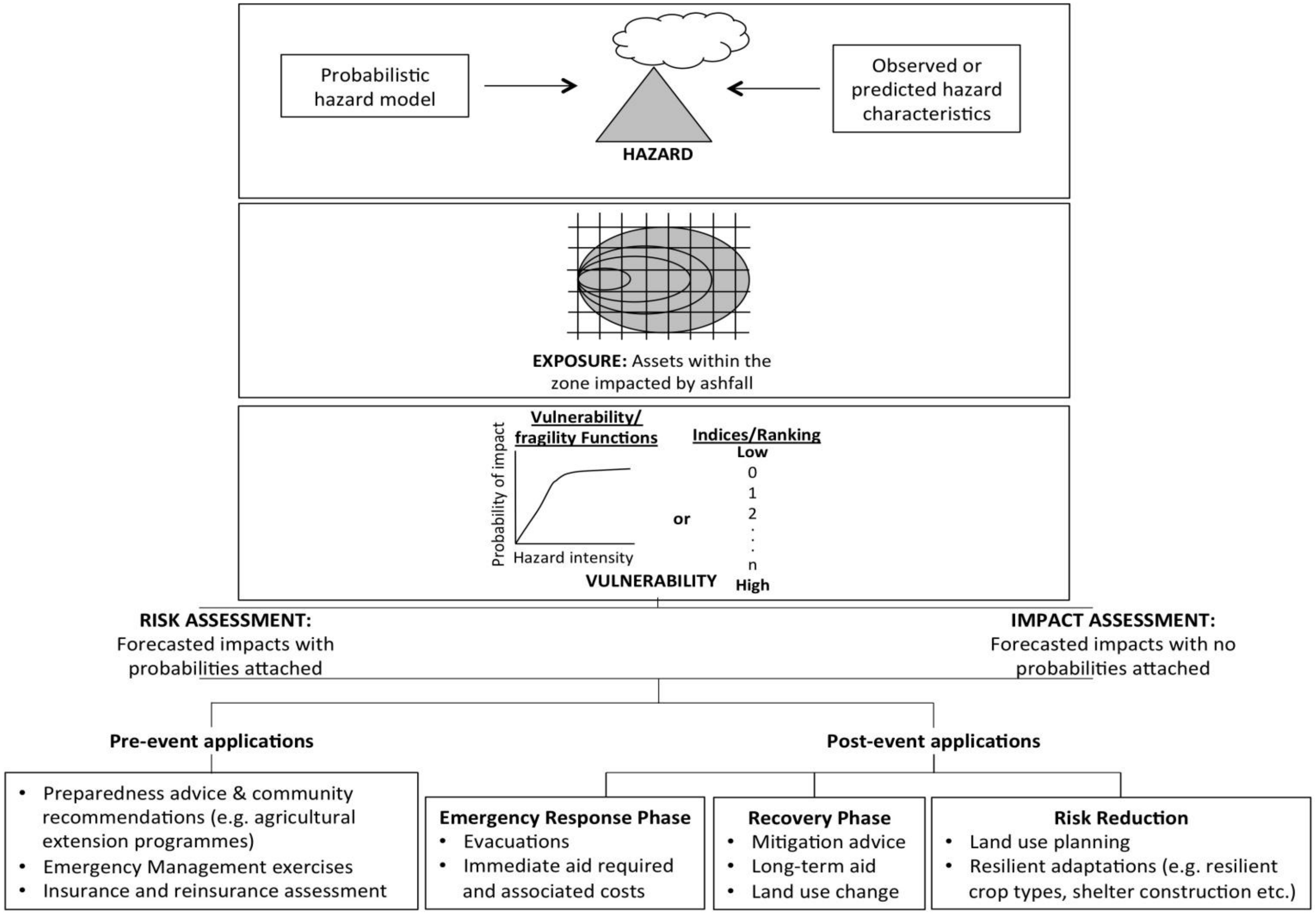

Figure 1.3: Diagram showing the relationship between impact and risk assessment and their associated inputs and outputs.

1.3.1 Purpose of impact assessments

One of the main objectives of impact assessments is providing information to emergency managers to coordinate and plan response post-event, to identify areas pre-event that will need evacuating, and help aid distribution planning (Alexander 2002) (Fig. 1.3). The insurance industry also uses pre- and post- impact assessments to refine more sophisticated risk modelling and also uses past damage costs from impact assessments to examine future event estimates (Friedman 1984; Mileti & Henry 1999). Post-event impact assessments play a vital role in providing the qualitative and quantitative data for vulnerability and risk assessments, and strengthening the understanding of possible hazard scenarios and the vulnerability characteristics of an area and their influence on loss. Pre-event impact assessments (EIA) provide predictive capacity where there is insufficient empirical and/or analytical data to accurately constrain the probabilities of outcomes, meaning that a full risk assessment is not possible. Inputs and outputs of impact and risk assessments are summarised in Figure 1.3.

1.3.2 Recording impact assessment information

Impact can be recorded in a range of ways which may include physical, economic, or social losses, and direct or indirect damage after a range of hazard scenarios (Smith, 2013). Post-event assessment of damage to buildings and infrastructure is commonly undertaken in a range of disciplines. Earthquake engineering has the most well documented methods, with assessment undertaken at various scales from response-based field work which assesses damage to individual structures (Bazzurro & Cornell 2004; Erdik et al. 2011; Ghobarah 1999; Rossetto et al. 2014), to remote sensing (Brunner et al. 2010; Chiroiu & Andre 2001). The core objective of post-event impact assessments is to assess the hazard intensity in space and time, what elements were exposed, the element's vulnerability characteristics, and observed impacts (Fig. 1.3). However, how the vulnerability of exposed assets influences the impacts appears to be consistently less comprehensively recorded than the effect of different hazard characteristics and intensities, particularly for volcanic hazard risk (Jenkins et al. 2014a).

This imbalance has been identified by various authors and needs addressing to improve the value and utility of future impact and risk assessments (both pre- and post-event), and ultimately to improve disaster risk management (Sparks et al. 2013; Wilson et al. 2014).

1.3.3 Relating HIM to impact information

Simplistic impact assessments are essentially exposure assessments, which relate hazard intensities (such as ground acceleration for earthquakes, or tephra thickness after a volcanic eruption) and exposed assets, in order to define what area is affected. Whilst this is a good rapid approach, the severity of impacts is not presented, which limits planning specific management strategies. Assessments can be improved by relating the hazard intensity to an estimated level of impact, depending on the vulnerability of the exposed system. Three main approaches have been used to relate hazard, exposure and vulnerability data to observed impacts:

1) Damage thresholds that estimate certain impacts which are likely to occur when certain hazard intensities are exceeded (e.g. Wilson et al. 2014). They often based on relatively limited or qualitative impact datasets;
2) Damage states provide a measure of common states of damage caused by the natural hazard and exposed element. They are typically offer greater explanation than damage thresholds and may be presented over a range of hazard intensities;
3) Fragility functions are equations which express the probability of differing levels of damage sustained for different elements as a function of chosen hazard intensity measure (Baker 2014).

Both damage threshold and damage state approaches are a way of standardising qualitative impact information within a quantitative scale with impact descriptors, in order to allow for comparisons and trends to be easily identified (Krausmann & Mushtaq 2008). Damage state and fragility function approaches have found favour because they allow for some forecasting of impacts to be undertaken with little hazard metric input. Whilst there are some limitations with applying a standardised index, they allow for damage across different areas to be compared within a framework. In some instances damage states have been connected with hazard intensity thresholds such as exceedance of a particular ground acceleration (Kircher & Nassar 1997), dynamic pressure within a pyroclastic density current (Spence et al. 2004), or the load of a tephra deposit (Jenkins et al. 2014a). These must be matched against the impacted element type (e.g., infrastructure sector, type of agriculture) and specific site characteristics, and assume that similar systems will mostly perform similarly under common hazard intensities. Variability of impacts can be taken into account by adding uncertainty bounds. Using a comprehensive understanding of impact to different element types, a series of damage states can be applied to a range of element inventories (e.g., various system designs for electrical systems, or types of agriculture). Where limited vulnerability data is available, broad homogenous element classes must be used which can reduce the applicability and resolution of the product of an impact or risk assessment. Connecting damage scales with more quantitative information about economic costs and vulnerability information is an ongoing area of research (Blong, 2003; Spence et al. 2005), and will allow for the refinement of impact assessment data.

Fragility functions are widely used in natural hazard impact and risk assessment, particularly in earthquake engineering (Rossetto et al. 2013; Rossetto et al. 2014). Large post-EIA building and infrastructure damage surveys, and empirical and analytical laboratory analysis help inform a broad array of fragility curves that minimise the associated uncertainties (Porter et al. 2007). There is strong desire to develop a similar set of resources for volcanic hazards, such as tephra fall, to allow for more accurate modelling and forecasting of loss (Wilson et al. 2012a; Jenkins et al. 2014b).

1.4 Agricultural impact assessment after tephra fall

Numerous agricultural impact assessment studies both before and after tephra fall events have been undertaken (Table 1.1). Pre-EIA has included the categorising of likely damage to agricultural systems at various tephra thicknesses (e.g., Jenkins et al. 2014b), as well as the development of fragility functions that can be used to numerically model agricultural loss (e.g., Wilson & Kaye 2007). Post-EIA have focussed primarily on local-scale, observational data collected from fieldwork and interviews with farmers and agricultural agencies, and more quantitative information on economic losses at a regional scale (Cronin et al. 1998; Wilson et al. 2007; Wilson et al. 2011a). Observational case studies after a tephra fall event have proven valuable to inform vulnerability analysis due to the complex nature of agricultural systems, complimented by some laboratory trials exploring specific aspects of HIM and VC (Wilson et al. 2014). Consistent methodologies of tephra impact assessments of agriculture have been developed over the past 15 years allowing broad trends in the influence of HIM and VC on impacts to be identified (Table 1.1), but no clear, widely-applied guidelines exist (Wilson, et al. 2014). However, there are protocols in place for the hazard assessment of leachable tephra chemistry developed by the International Volcanic Health Hazard Network (Stewart et al. 2013).

When considering tephra fall on agricultural systems, post-EIA for agriculture (Table 1.1; in particular Wilson et al. 2011a) have identified that the type and severity of impacts is dependent on: 1) the characteristics and intensity of the hazard experienced at a particular site (HIM), such as the tephra loading (i.e. kg/m^2), deposit thickness, grainsize, soluble chemistry, mechanical strength, etc.; broadly termed hazard intensity metrics; and 2) the characteristics of the exposed agricultural system(s) at that particular site (VC), such as the type of farm, production intensity, reliance on inputs (e.g. water, electricity, etc.), labour resources, etc.; called vulnerability characteristics. These factors operate at an individual farm level, as well as over regional scales, and combine and interact to produce the impacts to the agricultural region affected. Additionally impacts to other societal elements can cause cascading impacts to agricultural systems, such as loss of power preventing use of water pumps, or road closures hindering evacuation and transport of products (Wilson et al. 2014). This interdependency highlights the value of holistic assessments which consider infrastructure and primary industry impacts (Sword-Daniels et al. 2014; Wilson et al. 2012). The range of influential HIM, VC, and associated agricultural impacts is summarised in Figure 1.4.

The most recently developed, globally applicable damage state estimates for agricultural impacts due to tephra fall were developed as part of the Global Assessment Report 2015 (GAR-15) on Disaster Risk Reduction for the United Nations – International Strategy for Disaster Reduction (UN-ISDR) (Jenkins et al. 2014b). Five damage states are presented ranging from no damage (D0) to retirement of the previously productive land due to severe tephra inundation (D5). Tephra thicknesses commonly observed at each damage state were then assigned to each sector, based primarily on expert judgement. Whilst this is a useful pre-EIA tool that can be generally applied to a range of events, Jenkins et al. (2014b) acknowledge it does not take into account the influence that other HIM and VC unique to a particular agricultural system could have on the thickness thresholds for each damage state.

Agricultural fragility functions have been created for pastoral agriculture, horticulture and forestry for the New Zealand setting by Wilson & Kaye (2007). These curves estimate first-order economic losses to farms, separating losses into production and asset-bases. An account of changing seasonal vulnerability is also made by use of a coefficient dependent on time of year. In this case, most of the curve fitting was based on expert judgement rather than empirical data. Additionally, there was no consideration of the availability of equipment and assets that enable the application of mitigation techniques, which may substantially minimise losses for farms that can rapidly cultivate and/or irrigate after tephra fall.

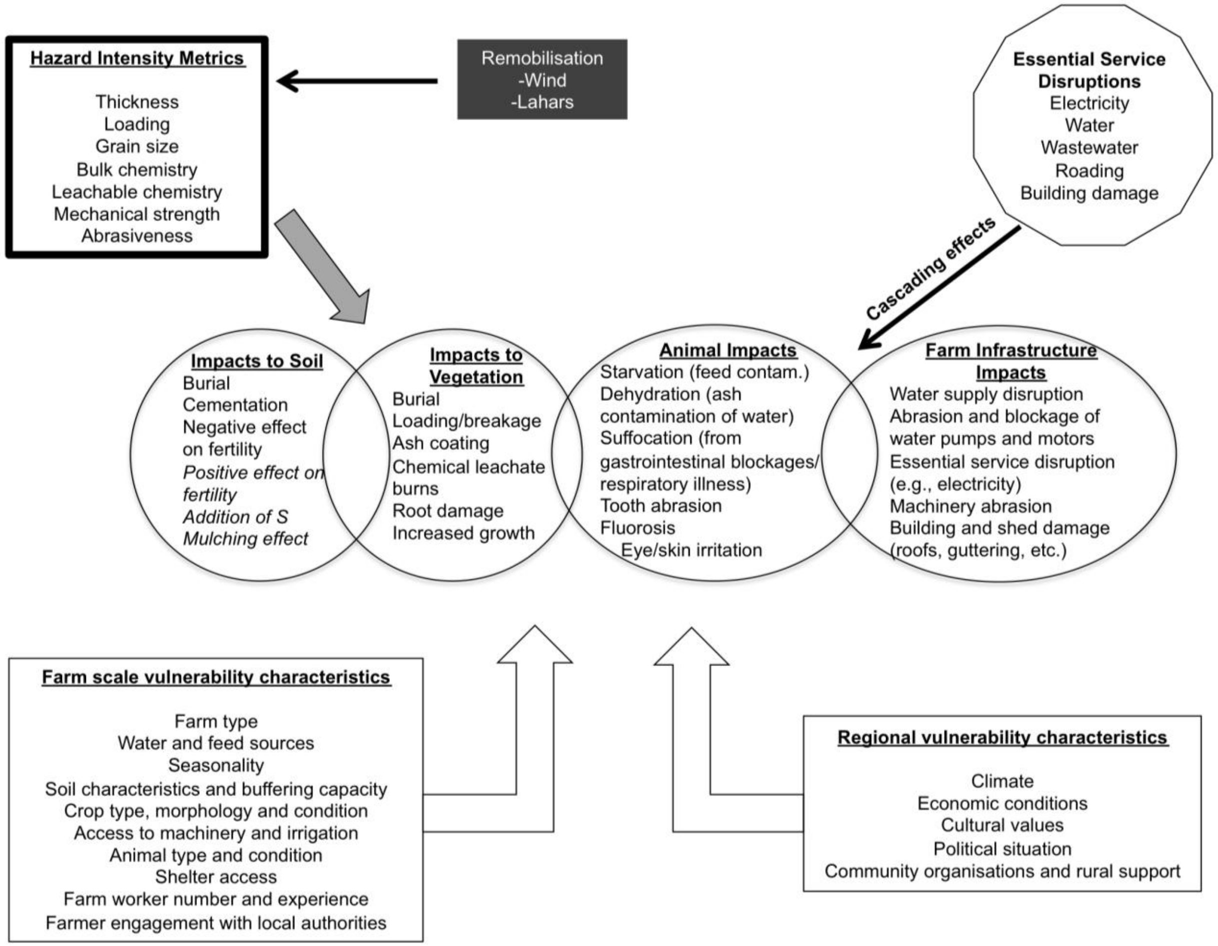

Figure 1.4: Figure showing the relationship between ashfall impacts, hazard intensity measures, and vulnerability characteristics for soil, vegetation and animals.

1.5 Thesis objectives

The aim of this thesis is to investigate how vulnerability characteristics influence tephra fall impact to agriculture. This aim is addressed by undertaking the research from a risk based perspective and is underpinned by the premise that effective assessment of risk is required to inform effective disaster risk management.

The three main objectives of the thesis are:

Development of an improved understanding of the factors that influence agricultural impacts from tephra fall

- Exploring the relationship between the intensity of the tephra hazard faced, the vulnerability of the affected agricultural systems, and the resulting impacts.
- Testing the applicability of previously proposed relationships between impacts and HIM (tephra thickness) (Wilson et al. 2014; Jenkins et al. 2014) (Chapter 2).
- Demonstrating a practical application of analysing the leachable element concentrations (an important HIM) from tephra particles using the IVHHN protocol; and applying the results to analyse the risk of the tephra fall to exposed agricultural systems (Chapter 3).
- Assessing the qualitative and quantitative relationships between HIM, VC, and agricultural production change and damage, using damage states (Chapter 4).

Standardisation of impact assessments through guidelines and an impacts database

Development of guidelines for initial data capture to provide a consistent evaluation of the impacts across multiple locations. The components of the protocol include:

- Identifying farmer’s and manager’s information needs after tephra deposition (Chapters 3 & 4).
- Finding the most accurate and timely methods with which to gather the required information on tephra characteristics (Chapters 3, 4, & 5).

- Impact assessment guidelines that document farm characteristics and impact occurrence, which can be rapidly deployed after an event and can be adapted to suit a range of environments and farming methods (Chapter 5; Section 2).
- Development of an agricultural impacts database to collate information gathered in a standardised manner in order to allow for comparisons and lessons to be drawn (Chapter 5; Section 3).

Progression of fragility functions to include different agricultural vulnerabilities due to farm type, intensity, seasonality, and leachable fluoride

Integrating recent post-event impact assessment data with previous published work to refine and create fragility functions that improve our impact forecasting ability (Chapter 6). Functions incorporate tephra thickness (as the main HIM), as well as vulnerability factors such as:

- farming styles,
- farm intensity,
- environmentally-available fluoride concentrations,
- and seasonality (i.e., the season that the event occurs during)

1.6 Thesis structure

In order to improve tephra fall impact assessment by developing quantitative vulnerability and impact models (Chapter 6) and impact assessment guidelines (Chapter 5), a series of case studies are presented. The 2011 Cordón Caulle volcanic complex (CC-VC) eruption was the primary eruption case-study used to: assess impacts to agricultural and critical infrastructure systems compared to those predicted by existing vulnerability models using tephra thicknesses (Chapter 2); and evaluate leachate chemistry and possible chemical toxicity (Chapter 3). This allowed for comparisons between what occurred after the tephra fall and what was expected based on the hazard characteristics of the tephra fall (tephra thickness and leachable chemistry). Assessing the relationship between impacts and traditional HIM (tephra thickness based impact assessment tools in Chapter 2, and leachable element concentrations in Chapter 3), further demonstrated that HIM are not always accurate at forecasting impacts when evaluated in isolation. Assessing the CC-VC impacts using existing impact and vulnerability models, identified that current models are limited due to their reliance on a single HIM and demonstrated the need for better integration of VC into impact forecasting and assessment. Building on the idea of including both HIM and VC to increase the accuracy of pre- and post-EIA and forecasting tools, Chapter 4 used three case study eruptions from Patagonian South America, the 2011 CC-VC, the 2008 Chaitén and 1991 Hudson eruptions to develop a tephra fall damage state scale for agriculture that integrated vulnerability (Chapter 4). Using the lessons from the case studies to identify the hazard and vulnerability properties that most influence impacts, an agricultural impacts database (AID) and post-EIA guidelines are proposed (Chapter 5). These were designed to ensure that the most important HIM and VC data is being collected in the field and also stored within a user-friendly database, with the post-EIA guidelines designed to ensure that an AID entry can be populated. The aim of these tools is to gather and collate the information necessary to refine forecasting tools such as fragility functions.

Finally, a set of new agricultural fragility functions are proposed (Chapter 6). These were created using the information collected from previous case studies (including Chapters 2, 3, and 4) and data collated to populate the AID. The proposed system of functions take into account numerous sources of agricultural vulnerability to tephra fall including: farm type, farm size, pastoral intensity, seasonality and leachable fluoride. This means that the functions can be applied to a wider range of agricultural settings and increases their predictive accuracy by taking into account a broader range of vulnerability sources. The main themes of improving assessment and forecasting capacities are advanced throughout the thesis, with case studies providing information for the development of impact assessment guidelines, the agricultural impacts database, and the proposed fragility functions.

The main part of the thesis comprises these five main chapters (Chapters 2-6) that are either submitted or intended for submission to peer-reviewed scientific journals. The thesis results and overall conclusions are a result of the author’s own research; however, contributions from co-authors have been vital, and individual contributions to all chapters are detailed within the preceding co-authorship statements.

Appendices A, B and C contains the primary data used to support conclusions drawn within Chapters 3, 4 and 6 respectively.

1.7 References

Alexander, D. (2002). Principles of emergency planning and management. New York: Oxford University Press.

Antos, J. A., & Zobel, D. B. (1985). Recovery of forest understories buried by tephra from Mt. St. Helens. Vegetatio, 64, 103–111.

Araya, O., Wittwer, F., Villa, A., & Ducom, C. (1990). Bovine fluorosis following volcanic activity in the southern Andes. Veterinary Record, 126(26), 641–642.

Arbalan, A., Mazaheir, M., Mowafi, H., Van Rooyen, M., Teimoori, F., & Abbasi, R. (2011). Impact of the 26 December 2003 Bam earthquake on activities of daily living and instrumental activities of daily living of older people. Prehospitalisation Disaster Medicine, 26(2), 99–108.

Ayris, P. M., & Delmelle, P. (2011). Volcanic and atmospheric controls on ash iron solubility: a review. Physics and Chemistry of the Earth, Parts A/B/C, 45-46, 103-112. http://doi.org/10.1016/j.pce.2011.04.013

Ayris, P. M., & Delmelle, P. (2012). The immediate environmental effects of tephra emission. Bulletin of Volcanology, 74(9), 1905–1936. http://doi.org/10.1007/s00445-012-0654-5

Baxter, P. J., Bernstein, R. S., & Buist, a S. (1986). Preventive health measures in volcanic eruptions. American Journal of Public Health, 76(3), 84–90.

Bazzurro, P., & Cornell, C. (2004). Guidelines for seismic assessment of damaged buildings. Retrieved from http://www.iitk.ac.in/nicee/wcee/article/13_1708.pdf

Blaikie, P., Cannon, T., Davis, I., & Wisner, B. (1994). At risk: Natural hazards, people's vulnerability and disasters (2nd Edition). Abingdom, Oxon: Routledge

Blake, D. M., Wilson, G., Stewart, C., Craig, H., Hayes, J., Jenkins, S. F., Wilson, T. M., Horwell, C. J., Daniswara, R., Ferdiwijaya, D., Andreastuti, S., Leonard, G. S., Hendrasto, M. & Cronin, S. (in review). Impacts of the 2014 eruption of Kelud volcano, Indonesia, on infrastructure, utilities, agriculture and health. GNS Science report.

Blong, R. J. (1984). Volcanic hazards: A sourcebook on the effects of eruptions. Sydney: Academic Press.

Brunner, D., Lemoine, G., & Bruzzone, L. (2010). Earthquake damage assessment of buildings using VHR optical and SAR imagery. IEEE Transactions on Geoscience and Remote Sensing, 48(5), 2403–2420.

Cashman, K. V., Sturtevant, B., Papale, P., & Navon, O. (2000). Magmatic fragmentation. In H. Sigurdsson, B. F. Houghton, S. R. McNutt, H. Rymer, & J. Stix (Eds.), Encyclopedia of Volcanoes (pp. 421 – 430). San Diego: Academic Press.

Chiroiu, L., & Andre, G. (2001). Damage assessment using high resolution satellite imagery: Application to 2001 Bhuj, India, Earthquake.

Collins, B. D., & Dunne, T. (1986). Erosion of tephra from the 1980 eruption of Mount St . Helens. GSA Bulletin, 97(7), 896–905.

Cook, R. J., Barron, J. C., Papendick, R. I., & Williams, G. J. (1981). Impact on agriculture of the Mount St. Helens eruptions. Science (New York, N.Y.), 211(4477), 16–22. http://doi.org/10.1126/science.211.4477.16

Cronin, S. J., Hedley, M. J., Smith, R. G., & Neall, V. E. (1997). Impact of Ruapehu ash fall on soil and pasture nutrient status 1. October 1995 eruptions. New Zealand Journal of Agricultural Research, 40(3), 383–395. http://doi.org/10.1080/00288233.1997.9513260

Cronin, S. J., Hedley, M. J., Neall, V. E., & Smith, R. G. (1998). Agronomic impact of tephra fallout from the 1995 and 1996 Ruapehu Volcano eruptions , New Zealand. Environmental Geology, 34(April), 21–30.

Cronin, S. J., Neall, V. E., Lecointre, J. A., Hedley, M. J., & Loganathan, P. (2003). Environmental hazards of Fluoride in volcanic ash : a case study from Ruapehu volcano , New Zealand. Journal of Volcanology and Geothermal Research, 121 (3-4), 271-291.

Dahlgren, R. A., Ugolini, F. C., & Casey, W. H. (1999). Field weathering rates of Mt . St . Helens tephra. Science, 63(5), 587–598.

Dale, V., Swanson, F., & Crisafulli, C. M. (2005). Ecological responses to the 1980 eruptions of Mt. St. Helens. Springer, New York.

Diaz, F., Jimenez, C. C., & Tejedor, M. (2005). Influence of the thickness and grain size of tephra mulch on soil water evaporation. Agricultural Water Management, 74(1), 47–55. http://doi.org/10.1016/j.agwat.2004.10.011

Dingwell, D. B., Lavallée, Y., & Kueppers, U. (2011). Volcanic ash: A primary agent in the Earth system. Physics and Chemistry of the Earth, Parts A/B/C, 2010–2012. http://doi.org/10.1016/j.pce.2011.07.007

Edwards, K. J., Dugmore, A. J., & Blackford, J. J. (2004). Vegetational response to tephra deposition and land-use change in Iceland: a modern analogue and multiple working hypothesis approach to tephropalynology. Polar Record, 40(2), 113–120. http://doi.org/10.1017/S0032247403003000

Eggler, W. A. (1963). Life of Paricutin Volcano, Mexico, eight years after ceased activity. American Midland Naturalist, 69(1), 38–68.

Erdik, M., Şeşetyan, K., Demircioğlu, M. B., Hancılar, U., & Zülfikar, C. (2011). Rapid earthquake loss assessment after damaging earthquakes. Soil Dynamics and Earthquake Engineering, 31(2), 247–266. http://doi.org/10.1016/j.soildyn.2010.03.009

Friedman, D. G. (1984). Natural Hazard Risk Assessment for an Insurance Program. The Geneva Papers on Risk and Insurance, 9(30), 57–128.

Fuchs, S., Birkmann, J., & Glade, T. (2012). Vulnerability assessment in natural hazard and risk analysis: current approaches and future challenges. Natural Hazards, 64(3), 1969–1975. http://doi.org/10.1007/s11069-012-0352-9

Georgsson, G., & Petursson, G. (1972). Flurosis of sheep caused by Helka eruption in 1970. In Fourth annual conference of the ISFE.

Ghobarah, A. (1999). Response-based damage assessment of structures. Earthquake Engineering & Structural Dynamics, 104(April 1998), 79–104.

Gislason, S. R., Hassenkam, T., Nedel, S., Bovet, N., Eiriksdottir, E. S., Alfredsson, H. A., Hem, C. P., Balogh, Z. I., Dideriksen, K., Oskarsson, N., Sigfusson, B., Larsen, G.

& Stipp, S. L. S. (2011). Characterization of Eyjafjallajokull volcanic ash particles and a protocol for rapid risk assessment. Proceedings of the National Academy of Sciences of the United States of America, 108(18), 7307–12. http://doi.org/10.1073/pnas.1015053108

Giuliani, A. R., Mattei, A., Santilli, F., Clori, G., Scatigna, M., & Fabiani, L. (2014). Well-being and perceived quality of life in elderly people displaced after the earthquake in L'Aquila, Italy. Journal of Community Health, 39(3), 531–7. http://doi.org/10.1007/s10900-013-9793-7

Hobbs, P. V., Radke, L. F., Eltgroth, M. W., & Hegg, D. A. (1981). Airbourne studies of the emissions from the volcanic eruptions of Mt St Helens. Science, 211(4484), 816–818.

Inbar, M., Ostera, H., Parica, C., & Remesal, M. (1995). Environmental assessment of 1991 Hudson volcano eruption ashfall effects on southern Patagonia region, Argentina. Environmental Geology, 25, 119–125.

ISDR. (2009). 2009 UNISDR Terminology on Disaster Risk Reduction. Geneva, Switzerland.

Jenkins, S. F., Spence, R. J. S., Fonseca, J. F. B. D., Solidum, R. U., & Wilson, T. M. (2014). Volcanic risk assessment: Quantifying physical vulnerability in the built environment. Journal of Volcanology and Geothermal Research, 276, 105–120. http://doi.org/10.1016/j.jvolgeores.2014.03.002

Jenkins, S. F., Wilson, T. M., Magill, C. R., Miller, V., & Stewart, C. (2014). Volcanic ash fall hazard and risk: Technical background paper for the UN-ISDR Global Assessment Report on Disaster Risk Reduction 2015. Retrieved from http://muse.jhu.edu/content/crossref/journals/mln/v120/120.3contributors.html

Johnston, D. M., Houghton, B. F., Neall, V. E., Ronan, K. R., & Paton, D. (2000). Impacts of the 1945 and 1995-1996 Ruapehu eruptions, New Zealand: An example of increasing societal vulnerability. Geological Society of America Bulletin, (5), 720–726.

Kabata-Pendias, A. (2001). Trace Elements in Soils and Plants. Boca Raton: CRC Press.
Kircher, C., & Nassar, A. (1997). Development of building damage functions for earthquake loss estimation. Earthquake Spectra, 13(4), 663–682. Retrieved from http://www.earthquakespectra.org/doi/abs/10.1193/1.1585974

Krausmann, E., & Mushtaq, F. (2008). A qualitative Natech damage scale for the impact of floods on selected industrial facilities. Natural Hazards, 46(2), 179–197. http://doi.org/10.1007/s11069-007-9203-5

Le Pennec, J., Ruiz, G. A., Ramón, P., Palacios, E., Mothes, P., & Yepes, H. (2012). Impact of tephra falls on Andean communities : The influences of eruption size and weather conditions during the 1999 – 2001 activity of Tungurahua volcano , Ecuador. Journal of Volcanology and Geothermal Research, 217-218(August 2006), 91–103. http://doi.org/10.1016/j.jvolgeores.2011.06.011

Leonard, G. S., Johnston, D. M., Williams, S., Cole, J. W., Finnis, K., & Barnard, S. (2005). Impacts and management of recent volcanic eruptions in Ecuador : lessons for New Zealand. GNS Science Report 2005/20.

Lin, M., Huang, W., Huang, C., Hwang, H., & Tsai, L. (2014). The impact of the Chi-Chi earthquake on quality of life among elderly survivors in Taiwan - A before and after study, Quality of Life Research, 11(4), 379–388.

Lindell, M. K., & Prater, C. S. (2004). Assessing Community Impacts of Natural Disasters, Natural Hazards Review, 4(4), 176-185.

Lyons, J. V. (1986). Agricultural impact and adjustment to the Mount St. Helens ashfall: a search for analogs. In S. Keller (Ed.), Mount St. Helens: five years later (pp. 423 – 429). Cheney: Eastern Washington University Press.

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M. L., & Di Ruocco, A. (2012). Basic principles of multi-risk assessment: a case study in Italy . Natural Hazards, Online First. http://doi.org/10.1007/s11069-012-0092-x

McLaren, R. G., & Cameron, K. C. (1996). Soil Science. Melbourne: Oxford University Press.

Mercado, R. A., Betram, J., Lacsamana, T., & Pineda, G. L. (1996). Socioeconomic impacts of the Mount Pinatubo eruption. In C. G. Newhall & R. S. Punongbayan (Eds.), Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines. Quezon City: University of Washington Press.

Meslem, A., Ayala, D. D., Ioannou, I., Rossetto, T., & Lang, D. (2014). Uncertainty and quality rating in analytical vulnerability assessment. In Second European conference on earthquake engineering and seismology (pp. 1–12). Istanbul.

Messner, F., & Meyer, V. (2005). Flood damage, vulnerability and risk perception - challenges for flood damage research. UFZ- Diskussionspapiere, No. 13/2005, 1-27.

Mileti, D., & Henry, A. J. (1999). Disasters by design: A reassessment of natural hazards in the United States. Washington D. C.: National Academies Press.

Neild, J., Flaherty, P. O., Hedley, P., Underwood, R., Johnston, D., Christenson, B., & Brown, P. (1998). Impact of a Volcanic Eruption on Agriculture and Forestry in New Zealand.

New South Wales Agriculture. (1999). Pastures and Acid Soils. Agriculture. Sydney.

Nolen-Hoeksema, S., & Morrow, J. (1991). A prospective study of depression and posttraumatic stress symptoms after a natural disaster: The 1989 Loma Prieta earthquake. Journal of Personality and Social Psychology, 61(1), 115–121. http://doi.org/10.1037//0022-3514.61.1.115

Pérez, F. L. (2009). The role of tephra covers on soil moisture conservation at Haleakala's crater (Maui, Hawai'i). Catena, 76(3), 191–205. http://doi.org/10.1016/j.catena.2008.11.007

Pondard, N., & Daly, M. (2011). Natural hazards risk modelling: an approach providing risk management solutions for local government. GNS Miscellaneous Series 38, 1-12.

Porter, K., Kennedy, R., & Bachman, R. (2007). Creating Fragility Functions for Performance-Based Earthquake Engineering. Earthquake Spectra, 23(2), 471–489. http://doi.org/10.1193/1.2720892

Rees, J. D. (1993). Effects on natural and agricultural vegetation. In F. Luhr & T. Simkin (Eds.), Paricutin: The volcano born in a Mexican cornfield (pp. 215–229). Pheonix, Arizona: Geoscience Press, Inc.

Rossetto, T., Ioannou, I., & Grant, D. N. (2013). Existing Empirical Fragility and Vulnerability Relationships: Compendium and Guide for Selection. Pavia, Italy.

Rossetto, T., Ioannou, I., Grant, D. N., & Maqsood, T. (2014). Guidelines for empirical vulnerability assessment. GEM technical report 2014-X, GEM Foundation, Pavia, Italy.

Schmidt, J., Matcham, I., Reese, S., King, A., Bell, R., Henderson, R., … Heron, D. (2011). Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling. Natural Hazards, 58, 1169–1192.

Seymour, V. A., Hinckley, T. M., Morikawa, Y., & Franklin, J. F. (1983). Foliage damage in coniferous trees following volcanic ashfall from Mt . St . Helens, 59(2/3), 339–343.

Shoji, S., Nanzyo, M., & Dahlgren, R. A. (1993). Volcanic Ash Soil. Amsterdam: Elsevier Science.

Smith, A. M., Coupland, G., Dolan, L., Harberd, N., Jones, J., Martin, C., … Amey, A. (2010). Plant Biology. New York: Garland Science.

Smith, D. I. (1994). Flood damage estimation - A review of urban stage-damage curves and loss functions. Water, 20(3), 231–239.

Smith, K. (2013). Environmental hazards: Assessing risk and reducing disaster (6th Ed.). New York: Routledge.

Smith, W. H., & Staskawicz, B. J. (1977). Removal of Atmospheric Particles by Leaves and Twigs of Urban Trees : Some Preliminary Observations and Assessment of Research Needs. Environmental Management, 1(4), 317–330.

Sneva, F., Britton, C., & Mayland, H. (1982). Mt. St. Helens Ash: Considerations of its fallout on rangelands. Retrieved from http://eprints.nwisrl.ars.usda.gov/1128/1/615.pdf

Sparks, R. J., Aspinall, W. P., Crosweller, H. S., & Hincks, T. K. (2013). Risk and uncertainty assessment of volcanic hazards. In Risk and uncertainty assessment for natural hazards (p. 558). Cambridge: Cambridge University Press.

Spence, R. J. S., Zuccaro, G., Petrazzuoli, S., & Baxter, P. J. (2004). Resistance of buildings to pyroclastic flows: analytical and experimental studies and their application to Vesuvius. Natural Hazards Review, 5(1), 48–59. http://doi.org/10.1061/(ASCE)1527-6988(2004)5:1(48)

Stewart, C., Horwell, C., Plumlee, G., Cronin, S., Delmelle, P., Baxter, P., Calkins, J., Damby, D., Morman, S., & Oppenheimer, C. (2013). Protocol for analysis of volcanic ash samples for assessment of hazards from leachable elements. IVHHN protocol; Durham University 2013.

Stewart, C., Johnston, D. M., Leonard, G. S., Horwell, C. J., Thordarson, T., & Cronin, S. J. (2006). Contamination of water supplies by volcanic ashfall: A literature review and simple impact modelling. Journal of Volcanology and Geothermal Research, 158(3-4), 296–306. http://doi.org/10.1016/j.jvolgeores.2006.07.002

Suttle, N. F. (2010). Mineral Nutrition of Livestock (4th ed.). Oxfordshire: CABI.

Sword-Daniels, V., Wardman, J., Stewart, C., Wilson, T., Johnston, D., & Rossetto, T. (2011). Infrastructure impacts, management and adaptations to eruptions at Volcán Tungurahua, Ecuador, 1999-2010. GNS Science report 2011/24, 73p.

Tejedor, M., Jiménez, C., & Díaz, F. (2003). Volcanic materials as mulches for water conservation. Geoderma, 117(3-4), 283–295. http://doi.org/10.1016/S0016-7061(03)00129-0

Thorarinsson, S. B. (1969). The Lakagigar Eruption of 1783. Bulletin of Volcanology, 33(3), 910–929.

Thorarinsson, S. B. (1979). Damage caused by volcanic eruptions. In P. D. Sheets & D. K. Grayson (Eds.), Volcanic activity and human ecology (pp. 125–159). New York: Academic Press.

Thorarinsson, S. B., & Sigvaldason, G. E. (1971). The Hekla eruption of 1970. Bulletin of Volcanology, 36(2), 269–288.

Tilling, R. I. (2005). Volcano Hazards. In J. Marti & G. G. Ernst (Eds.), Volcanoes and the Environment (p. 55). Cambridge: Cambridge University Press.

Uexkull, H. R. von, & Mutert, E. (1995). Global extent, development and economic impact of acid soils. Plant and Soil, 171(1), 1–15. http://doi.org/10.1007/BF00009558

Ugolini, F., & Dahlgren, R. (2002). Soil development in volcanic ash. Global Environmental Research, 69–81.

UNISDR. (2015). Sendai Framework for Disaster Risk Reduction 2015 - 2030. http://www.wcdrr.org/preparatory/post2015-08-06

Van der Sande, C. J., de Jong, S. M., & de Roo, a. P. J. (2003). A segmentation and classification approach of IKONOS-2 imagery for land cover mapping to assist flood risk and flood damage assessment. International Journal of Applied Earth Observation and Geoinformation, 4(3), 217–229. http://doi.org/10.1016/S0303-2434(03)00003-5

Varekamp, J. C., Luhr, J. F., & Prestegaard, K. L. (1984). The 1982 eruptions of El Chichón volcano (Chiapas, Mexico): Character of the eruptions, ash-fall deposits, and gasphase. Journal of Volcanology and Geothermal Research, 23(1-2), 39–68.

Veneklaas, E. (1990). Nutrient fluxes in bulk precipitation and throughfall in two montane tropical rain forests, Colombia. The Journal of Ecology, 78(4), 974–992.

Wang, B., Michaelson, G., Ping, C.-L., Plumlee, G., & Hageman, P. (2010). Characterization of Pyroclastic Deposits and Pre-eruptive Soils following the 2008 Eruption of Kasatochi Island Volcano, Alaska. Arctic, Antarctic, and Alpine Research, 42(3), 276–284. http://doi.org/10.1657/1938-4246-42.3.276

Wardman, J. B., Wilson, T. M., Bodger, P. S., Cole, J. W., & Stewart, C. (2012). Potential impacts from tephra fall to electric power systems: a review and mitigation strategies. Bulletin of Volcanology, 74(10), 2221–2241. http://doi.org/10.1007/s00445-012-0664-3

White, J. D. L., & Houghton, B. F. (2006). Primary volcaniclastic rocks. Geology, 34(8), 677. http://doi.org/10.1130/G22346.1

Wilson, G., Wilson, T. M., Deligne, N. I., & Cole, J. W. (2014). Volcanic hazard impacts to critical infrastructure: A review. Journal of Volcanology and Geothermal Research, 286, 148–182. http://doi.org/10.1016/j.jvolgeores.2014.08.030

Wilson, T., Cole, J., Cronin, S., Stewart, C., & Johnston, D. (2011a). Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: lessons for recovery. Natural Hazards, 57(2), 185–212. http://doi.org/10.1007/s11069-010-9604-8

Wilson, T., Cronin, S., Cole, J., & Johnston, D. (2009). Impacts and rehabilitation of pasture following volcanic ashfall. In Vulnerability of pastoral farming systems to volcanic ashfall hazards (pp. 71–126). University of Canterbury, PhD Thesis.

Wilson, T., & Kaye, G. (2007). Agricultural fragility estimates for volcanic ash fall hazards. GNS Science report 2007/37.

Wilson, T., Kaye, G., Stewart, C., & Cole, J. (2007). Impacts of the 2006 eruption of Merapi volcano, Indonesia, on agriculture and infrastructure. GNS science report 2007/07, 69p.

Wilson, T. M., & Cole, J. W. (2007). Potential impact of ash eruptions on dairy farms from a study of the effects on a farm in eastern Bay of Plenty, New Zealand; implications for hazard mitigation. Natural Hazards, 43(1), 103–128. http://doi.org/10.1007/s11069-007-9111-8

Wilson, T. M., Cole, J. W., Stewart, C., Cronin, S. J., & Johnston, D. M. (2011b). Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. Bulletin of Volcanology, 73, 223–239. http://doi.org/10.1007/s00445-010-0396-1

Wilson, T. M., Stewart, C., Cole, J. W., Johnston, D. M., & Cronin, S. J. (2009). Vulnerability of farm water supplies to volcanic ash. GNS Science Report 2009/01.

Wilson, T. M., Stewart, C., Sword-Daniels, V., Leonard, G. S., Johnston, D. M., Cole, J. W., … Barnard, S. T. (2012). Volcanic ash impacts on critical infrastructure. Physics and Chemistry of the Earth, Parts A/B/C, 45-46, 5–23. http://doi.org/10.1016/j.pce.2011.06.006

Witham, C., Oppenheimer, C., & Horwell, C. (2005). Volcanic ash-leachates: a review and recommendations for sampling methods. Journal of Volcanology and Geothermal Research, 141(3-4), 299–326. http://doi.org/10.1016/j.jvolgeores.2004.11.010

Zheng, S. J. (2010). Crop production on acidic soils: overcoming aluminium toxicity and phosphorus deficiency. Annals of Botany, 106(1), 183–4. http://doi.org/10.1093/aob/mcq134

Chapter Two

Impacts to agriculture and critical infrastructure in Argentina after tephra fall from the 2011 eruption of Cordón Caulle volcanic complex: An assessment of published damage and function thresholds

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2.1 Abstract

The 2011 Cordón Caulle (Chile) eruption dispersed tephra fall over 75,000 km^2 of land in Central Argentina. The large silicic eruption effected large parts of the Neuquén, Río Negro, and Chubut provinces, including the urban areas of Villa la Angostura, Bariloche and Jacobacci. These regions all received damage and disruption to critical infrastructure and agriculture due to the tephra fall. We describe these impacts and classify them according to published damage/disruption states (DDS). DDS for infrastructure and agriculture were also assigned to each area using the tephra thickness thresholds suggested by previous studies reported in the volcanological literature. The objective of this study was to evaluate whether the impacts were as expected based on the DDS suggested thresholds, and to determine whether other factors, apart from

tephra fall thickness, played a part. DDS thresholds based on tephra thickness were a good predictor of the impacts that occurred in the semi-arid steppe area around Jacobacci. This was unexpected as the more severe impacts were related to the challenging environmental conditions (low precipitation levels, high levels of wind erosion) and the daily wind remobilisation that occurred, rather than the tephra fall thicknesses received. The temperate region, including Villa la Angostura and Bariloche, performed better than the DDS assigned by tephra fall thickness suggested. Despite deposits as thick as 300 mm, full recovery occurred within months of the tephra fall event. The DDS scales need to incorporate a wider range of system characteristics, and environmental and vulnerability factors, as we propose here.

2.2 Introduction

Tephra fall is commonly the most widespread hazard to occur after an explosive eruption (Dingwell et al. 2011). Tephra fall can be highly disruptive and potentially damaging to many sectors of society, including critical infrastructure and agricultural systems. This means that the likely impacts of a tephra fall event need to be well understood and planned for in order to minimise disruption and damage (Wilson et al. 2012a).

The use of risk and impact modelling in order to better predict impacts means there is a growing need for accurate vulnerability information. Risk modelling quantifies the likelihood of impacts occurring using a probabilistic hazard model (ISDR 2009). In contrast, pre-event impact assessments (pre-EIA) predict the impacts from an event but do not have numerical probabilities attached to them. These both require information about the susceptibility of a specific system to the impacts, which may be captured by a vulnerability assessment (G. Wilson et al. 2014). Impact and associated vulnerabilities can be assessed by empirical (observations, previous case studies) and analytical (simulations, experiments) approaches. A method commonly applied after an tephra fall event is post-event impact assessment (post-EIA) which empirically or analytically assess the impacts on exposed societal elements (e.g., water and power supplies and agricultural production), as well as the hazard (e.g., tephra fall thickness/loading, grainsize, surface chemistry) and vulnerability characteristics (e.g., infrastructure design, farming style, access to mitigative measures) that influenced the impact. Numerous impact assessments have been conducted after tephra fall events, focussing on the impacts to critical infrastructure, electricity systems, water systems, and agriculture (for a list of post-EIA see T. Wilson et al. 2014).

Damage or disruption states (DDS) are a method of summarising and organising impact data during post-EIA, and predicting impacts in pre-EIA and risk assessments (Blong 2003a). These states use a common scale and have qualitative indicators assigned to each level, allowing for observational data to be placed on a numerical scale (Blong 2003b). Additionally, average expected or observed hazard intensity metrics (usually tephra fall thickness) have been assigned to many DDS schemes, in order to allow for the prediction of what DDS is likely to occur at a given hazard intensity (Jenkins et al. 2014; G. Wilson et al. 2014). This means DDS can be employed in pre-event impact forecasting in conjunction with hazard models. This usage requires some assumptions, as DDS do not take into account other measures of hazard intensity (e.g., tephra fall thickness, deposit density, grain size, surface chemistry), existing vulnerabilities of system designs (e.g., type of systems, areas where components are exposed to tephra fall), or mitigation measures (e.g., cleaning equipment, specific systems designed for tephra fall resilience) that may be in place. Tephra DDS schemes are typically focused on the characteristics of the hazard and have limited if any acknowledgement of the range of vulnerability characteristics that may influence impacts to the exposed societal elements that are being assessed. The small number of well-documented case studies available, and the inconsistent level of detail between different case studies also limit available schemes. Additionally, many DDS have been developed from specific case studies of an eruption or for a particular application, with little reflection on their utility in a broader application. Yet with increasing use of volcanic hazard DDS schemes, including at regional and global scales (e.g. Jenkins et al. 2014) the review of their predictive capacity is appropriate and necessary.

Tephra fall from the 2011 Cordón Caulle Volcanic Complex (CC-VC) eruption affected large areas of the Argentinian provinces of Neuquén, Río Negro, and Chubut (covering

75,000 km^2) (Buteler et al. 2011), and thus presented an opportunity to assess the impacts at different tephra fall thicknesses, and draw comparisons with previous case studies. In this study we will:

- Assess and qualitatively describe the impacts to critical infrastructure and agriculture after the eruption.
- Categorise the interview data collected using a range of DDS schemes (e.g., Jenkins et al. 2014; Neild et al. 1998; G. Wilson et al. 2014; Wilson et al. 2009).
- Assign the same DDS based on the tephra fall thicknesses received.
- Compare the DDS assigned to areas based on the qualitative data collected during post-EIA to the DDS assigned based on the tephra fall thickness thresholds given to each by their authors.

This will allow for the assessment of whether impacts were as expected given the hazard intensity experienced, and provide insights into the vulnerabilities, system design factors, and mitigation measures that may have contributed to any differences in impact.

2.2.1 2011 Cordón Caulle Eruption

The eruption sequence began with a swarm of volcano-tectonic earthquakes detected under the volcanic complex on the 27th April 2011 (OVDAS-SERNAGEOMIN, 2011). These earthquakes continued to increase in magnitude and frequency until June 4th when the eruption sequence began with a series of Plinian style phases (Schipper et al. 2012). A 5 km wide ash and gas plume rose to 12.2 km height. While lava was not initially observed, pyroclastic flows were noted. Prior to 2011, the last eruption from this centre was in May 1960, 38 hours after the main shock of the M9.5 earthquake in Valdivia, Chile (Smithsonian 2014). Eruptive activity continued throughout June and into July. Ash and gas plumes continued to erupt up to 13 km high. Tephra particles were detected on air quality monitoring filters in Porto Alegre, Brazil, over 2000 km to the northeast of the vent, on 9 and 14 June (de Lima et al. 2012). Long-range transport of the tephra plume led to flight disruptions in New Zealand, Australia and South Africa in late June and early July (Smithsonian 2014).

2.2.2 Study Area

This study focussed on the impacts due to tephra fall within the Northern Patagonia regions of Chile and Argentina. Within the study area were two distinct environmental zones: the Villa la Angostura, Parque Nacional Nahuel Huapi (Nahuel Huapi National Park), and Bariloche areas (including the Chile-Argentina border) and the steppe region (including Jacobacci and the Comallo Valley), Argentina (Fig. 2.1).

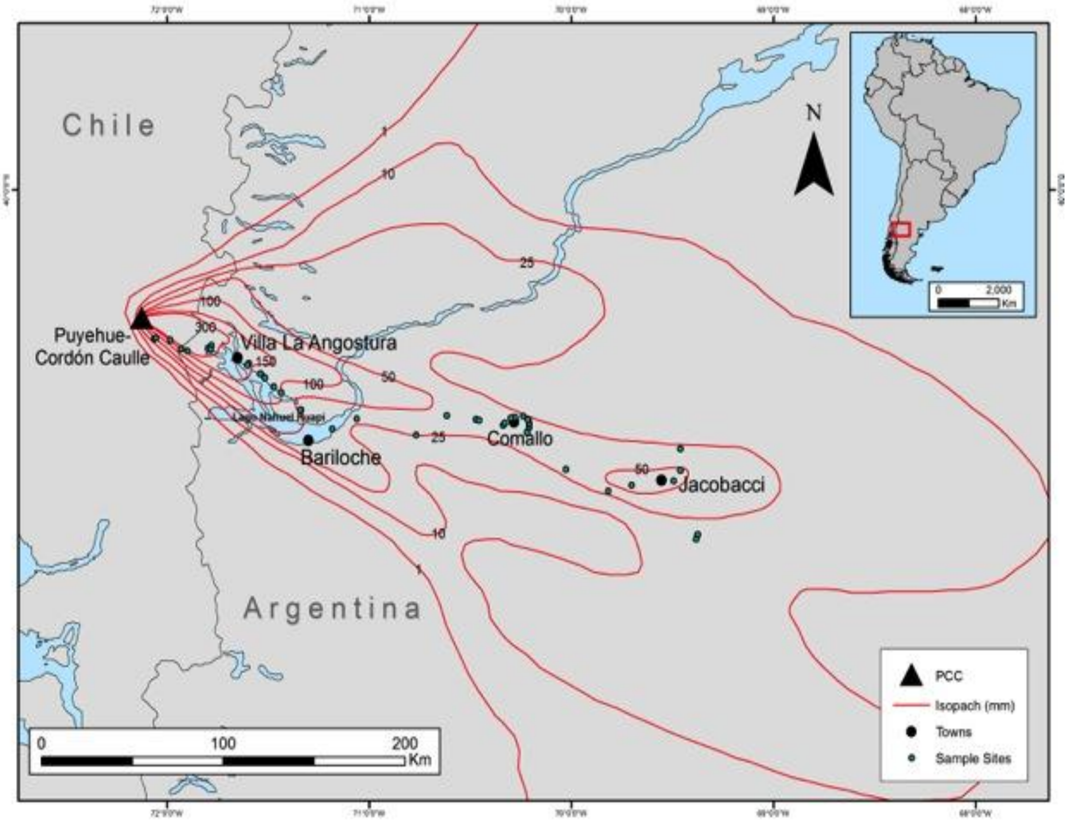


Figure 2.1: Map of tephra isopachs (adapted from Collini et al., 2012; converted to fall depth in mm, using 0.5 g/cm^2 average density (INTA 2011)) from 4 June 2011 eruption of CC-VC and main population centres affected. Interview and sampling sites visited by research team are shown as larger black dots.

The Nahuel Huapi National Park is a temperate, highland climatic area (Peel et al. 2007), that receives between 800 and 4000 mm of precipitation per annum (Servicio Meteorologico Nacional, 2012). In contrast the semi-arid steppe and Jacobacci (Peel et al. 2007), receives less than 300 mm precipitation per annum (Salazar et al. 1982). However, in the 6 years prior to the tephra fall, rainfall levels were much lower than this

(<160 mm/year) leading to drought conditions in the region (Departamento Provincial de Aguas 2011). The three main population centres of Villa la Angostura, Bariloche, and Jacobacci (Table 2.1; Fig. 2.1) were affected by varying thicknesses of tephra fall (Fig. 2.2).

Figure 2.2: Tephra sample site photographs illustrating the difference in tephra thicknesses and grain sizes along the deposit transect (see Fig. 2.1 for locations). A) coarse tephra near Villa la Angostura (53km from vent, 290mm thickness); B) medium grained tephra near Bariloche (100 km from vent, 30mm thickness); C) fine tephra in the steppe region near Jacobacci (240 km from vent, 40mm thickness).

Table 2.1: Characteristics of towns in the study area and tephra exposure from 2012 CC-VC eruption**.**

Town	Population (at 2010 census)	Depth of tephra fall (mm)	Distance from CC-VC	Description
Villa la Angostura	11,063	150-170 mm	54 km ESE	Located in a temperate zone towards the northern end of Lago Nahuel Huapi. The town experiences strong seasonal increases in population due to influxes of tourists. Its economy is based on tourism.
San Carlos de Bariloche	112,887	30-45 mm	~100 km SE	Bariloche is located on the southern shore of Lago Nahuel Huapi.
Ing. Jacobacci	6,261	~50 mm (fine tephra sized)	240 km ESE	Located on the semi-arid steppe. Primarily an agricultural service town.

2.2.3 Damage/disruption states

The most widely applied DDS scales for critical infrastructure impacts are taken from Wilson et al. 2014, and Jenkins et al. 2014. Each of these scales was developed using a combination of previous case study data, empirical information, and expert elicitation. For agricultural impacts, the most detailed agriculture-specific DDS system is outlined in Jenkins et al. (2014). These are based on previous experimental and theoretical studies and were compiled as part of the UN-ISDR Global Assessment Report on Disaster Risk Reduction. Additionally, tephra fall thickness thresholds, which can also be compared to CC-VC, have previously been placed on expected agricultural impacts by using a range of case studies (Wilson et al. 2009). These were developed based on field trials and numerous case studies. Initial attempts to place hazard intensity thresholds on clean-up actions are also applied to the three main towns affected by the CC-VC tephra fall (Hayes et al. *in prep*). DDS were applied to the CC-VC impacted sectors regionally and based on the maximum damage that occurred due to the tephra fall.

Table 2.2: Review of previous damage/disruption states for agriculture and infrastructure systems after tephra fall. Main classification systems used in this study in bold.

Proposed in	Type	Sectors	Main case studies and data sources	Number of states	Hazard threshold type	Strengths	Weaknesses
Blong 1984	Hazard intensity thresholds	All - notably agriculture (livestock health and horticultural crops)	Mt St Helens	5	Tephra fall thickness	Qualitative statements about animal health, also done for horticultural crops not seen in the CC-VC area	Information not placed within a specific damage state framework, does not acknowledge starvation, gastrointestinal blockages or feed supply issues
Neild 1998	Hazard intensity thresholds	Agriculture (vegetation focus)	Mt St Helens, Ruapehu	3	Tephra fall thickness	Part of a agriculture specific report, ideal for intended setting of New Zealand	Only 3 levels, so results within each are very generalised
T. Wilson et al. 2009	Hazard intensity thresholds	Agriculture (pastoral focus)	Ruapehu, Hudson, Chaiten	5	Tephra fall thickness	Based on review of numerous case studies and authors own field work	Generalised descriptions based on relatively high-intensity farming systems
G. Wilson et al. 2014	Damage and functionality states	Electrical, water, wastewater, transportation	Chaiten, Mt St Helens, CC-VC	4 (including 0)	Tephra fall thickness	Supported by numerical relationships between thickness and functionality	Assume a relatively standard system of infrastructure design
Jenkins et al. 2014	Damage and disruption states	All	Various	6 (including 0)	Tephra fall thickness	Includes all infrastructure sectors and agriculture, based on both prior case studies and expert elicitation	Descriptions are very generalised, and have not yet been widely applied
Hayes et al. 2015	Hazard intensity thresholds	Clean-up	Shinmoedake, Sakurajima, Mt St Helens	4	Tephra fall accumulation	First comprehensive review of clean-up operations	Likely to differ dependent on a cities previous experiences with tephra fall, and access to resources

Although not assessed in detail in this study, there have been numerous previous attempts to try and match qualitative impact data with hazard intensity thresholds such as tephra fall thickness (Table 2.2). Blong (1984) began this work by recording impacts observed across numerous case studies and sectors and the associated hazard intensities. Whilst this did not result in true DDS, some crude thresholds were proposed (notably for agriculture), and recognition of the range of impacts that could occur due to tephra fall led to increased recording of these indicators. Another approach was presented by Johnston (1997), where a vulnerability index was assigned to each sector at various tephra fall depths, based on the likelihood of a sector, a) 'becoming inoperable' and b) receiving 'damage.' This index was used to classify vulnerabilities for a specific geographic area in the North Island of New Zealand, and then used with various scenarios to predict impacts. This approach is useful as it considers the variations in infrastructure design and resilience across different areas, however it is reliant on specialist knowledge about the design and relative resilience of numerous sectors for each location. As this scheme's main utility as a New Zealand-specific, pre-EIA tool this system will not be applied in this study. An earlier attempt at placing hazard intensity thresholds on agricultural losses also exists (Neild et al. 1998). The major focus of this is on vegetation loss of both pasture and horticultural loss, however the full range of agricultural impacts is not captured and only three broad grouping of impacts are used (Table 2.2). Despite these limitations, these studies formed the basis of the current DDS schemes that will be applied in this study.

2.3 Methods

2.3.1 In-field impact assessment

Impacts to infrastructure and pastoral systems were assessed during a three-week long impact assessment trip undertaken by the authors between 27 February and 16 March 2012; approximately nine months after the initial eruption sequence began. Semi-structured, participant-led interviews were conducted with infrastructure managers, emergency managers, municipal officials and agricultural scientists in Villa la Angostura, Bariloche and Jacobacci. Five farmers were also interviewed. Interviews were conducted in Spanish through a trusted interpretor with previous experience in both interpretation of research interviews and in the Latin American setting. The translator was briefed on participant privacy, and the need to avoid social and psychological lines of questioning. Participants were required to complete and review a consent form available in Spanish. Data for this study was primarily collected during impact assessment study visits in areas exposed to tephra fall after the three eruptions (summarised in Table 4.3). Questions were separated into those for urban infrastructure managers and rural production managers and farmers (Table 2.3). Follow up questions on technical or contextual points were used as required. Interview methodology was reviewed and approved by the University of Canterbury Human Ethics Committee (2012/15).

2.3.2 Damage/disruption state application

Damage and disruption states were applied in two ways post-event. Firstly they were applied to regional and municipal critical infrastructure and agricultural sectors using the observational and impact data collected in the field. Secondly, scales were applied to the impacted regions solely based on the tephra fall thicknesses received. This approach relies upon the accuracy of published tephra fall thickness measurements at each of the assessed sites (Fig. 2.1). Municipal and infrastructure staff reported thicknesses within the range of those published (Table 2.1). However, tephra thicknesses were consistently over estimated by farmers (Table 2.4), possibly due to misperception and localised over-thickening and dune formation (Wilson et al. 2012a). In these two approaches DDS were used both as a method of categorising post-EIA observations, and assessing how well average tephra fall thicknesses predicted the CC-VC tephra fall impacts.

2.4 Tephra impacts and damage/disruption state assessment

2.4.1 Agriculture

Pastoral farming style and production techniques vary widely within the depositional area of the tephra fall, from small, dispersed operations in parklands of Parque Nacional Nahuel Huapi (Nahuel Huapi National Park), to extensive production on the arid steppe

(Jacobacci and Comallo areas). Thus the impacts of the tephra fall, recovery paths and mitigation options are also variable. The main control on the different agricultural types and intensities is the temperate (Nahuel Huapi) and the semi-arid (Jacobacci/Comallo) zones (Fig. 2.3). Interviews took place at five main farm sites with farm owners (Fig. 2.4; Table 2.4), with interviews with two regional production managers and two groups of agricultural agency scientists also providing information.

Table 2.3: Interview question schedule.

Urban Interviews **(infrastructure managers, municipal managers and staff, researchers)**	**Rural Interviews** **(farmers, agricultural agency staff, municipal production managers)**
Amount and description of tephra fall in area?	The urban interview questions were also used in rural interviews, with the addition of the following questions:
Wind/water remobilisation observed?	Farm size?
How did it affect your day-to-day life?	Annual production?
Were water supplies affected?	Animal numbers?
Building damage?	Changes in soil fertility?
Power supply disruption?	Any treatments for plants and to protect animals used?
Any communication issues?	Animal/crop losses sustained?
How was tephra cleaned-up?	What supplementary food has been used?
Stabilization techniques?	How has the tephra fall changed the way the area is farmed?
Tephra dump locations?	What warnings were given before the tephra fall?
Mitigation techniques employed?	Were any animals evacuated?
Any evacuations?	Details of animal movement
What emergency information was given by authorities?	
How was this communicated?	

Previous studies have identified the following issues for livestock arising from tephra contamination of feed: starvation due to feed becoming unpalatable; gastrointestinal and rumen blockages following tephra ingestion; and tooth abrasion (Cook et al. 1981; Cronin et al. 1998; Wilson et al. 2011b). These issues were all observed to some degree in this study. However, the main cause of livestock losses across the impacted area was due to starvation and gastrointestinal blockages. Some livestock were also affected by skin and eye irritations and infections (Robles 2012), possible chronic fluorosis (Flueck

& Smith-Flueck 2013; Flueck 2014; Flueck 2013), and in Jacobacci there was a decline in wool quality and shearing rates (Aguirre 2012; Easdale et al. 2014; Wilson et al. 2012b).

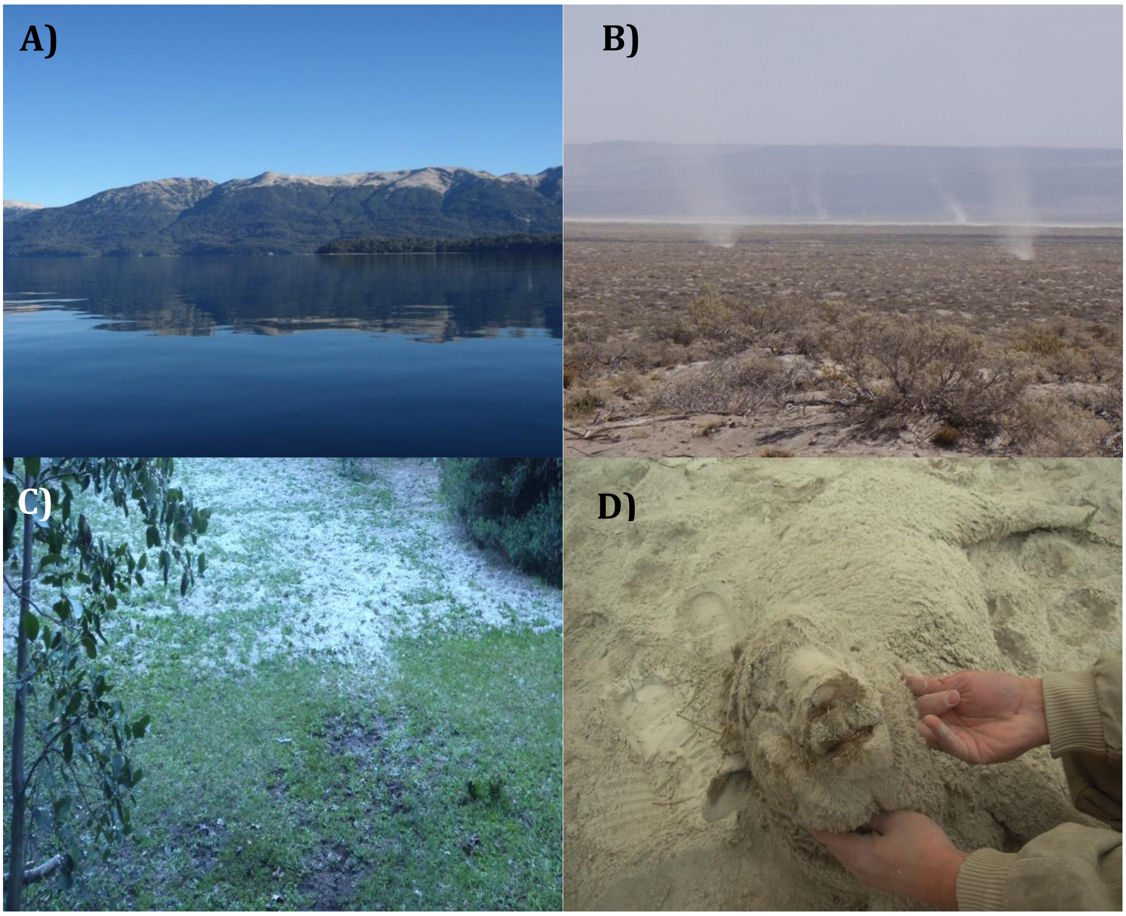


Figure 2.3: A) temperate region of Lago Nahuel Huapi and Nahuel Huapi National park; B) agricultural area near Jacobacci on the semi-arid steppe; C) tephra-covered clearing used by grazing animals within the Nahuel Huapi National Park, nine months after initial eruption; D) tephra covered sheep that farmer believed died of starvation near Jacobacci (Photo credit: Ailen Rodriguez).

Maintaining clean feed supplies was considerably more challenging in the steppe region where severe wind remobilisation of the tephra fall deposit began immediately and persisted for over 12 months. Drought conditions prior to the tephra fall also contributed to the increase in losses sustained in the steppe region (>40%) compared to the temperate, Nahuel Huapi National Park area. Drought on the steppe left pasture and livestock in poor condition, feed supplies depleted, and farm systems vulnerable. In contrast, losses in the national park area were more manageable as they were similar to those sustained after a severe winter (~25%; Table 2.4). This was due to higher rainfall rates rinsing feed and speeding tephra incorporation into soil, better animal condition leading into the event, and more livestock evacuations taking place. This grouping of agricultural losses by climatic zones is similar to what was observed after the 1991 Hudson eruption, where despite receiving lower levels of tephra fall, production losses on the semi-arid steppe were higher than expected due to continued wind remobilisation (Wilson et al. 2011b).

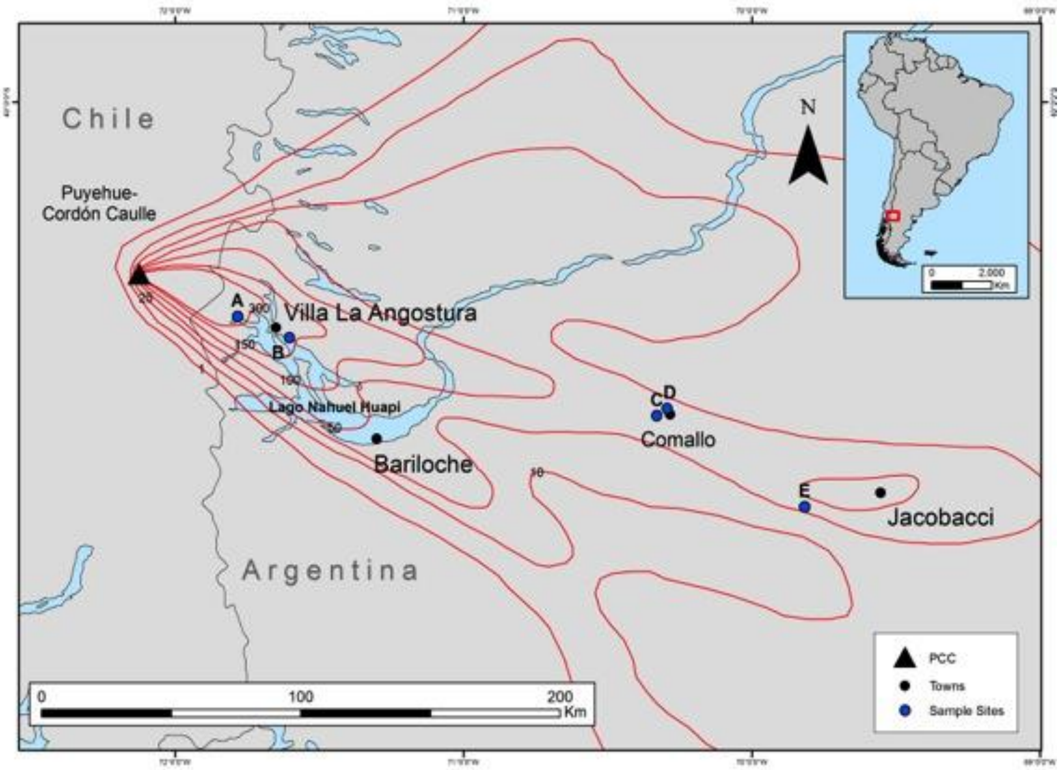


Figure 2.4: Map of sites (A-E) where in-depth farmer interviews were undertaken.

Table 2.4: Impacts on agriculture at study sites (NHNP* indicates Nahuel Huapi National Park land).

	Farm characteristics				Tephra Thickness (mm)		Animal Numbers (Losses in brackets)		
Farm ID	**Location**	**Farm Size (ha)**	**Approximate rainfall (mm/yr)**	**Animal water source**	**Farmer Est.**	**Wilson et al. 2012**	**Cows**	**Sheep**	**Goat**
A	Rio Totoral	NHNP	800	Stream/lake	600	300+	~50 (~46)	-	-
B	Eastern side of Lago Nahuel Huapi	NHNP	800	Stream/lake	500	300+	~50	-	-
C	Comallo Valley	1000	120	Troughs from underground wells	70	50	50	164 (121)	-
D	Outskirts of Comallo Township	10	120	Troughs from underground wells	30-40	30-45	-	20-30 (5)	-
E	Eastern end of the Comallo Valley	40	120	Troughs from underground wells	20	50	200 (35)	1600 (400)	-

*Farmers in the Nahuel Huapi National Park (NHNP) are assigned parcels of land based on animal numbers and the number of animals already in the immediate area. Land boundaries are not strictly adhered to and animals freely graze the park.

	Animal Symptoms							Vegetation Issues	
Farm ID	**Eye and skin irritation**	**Immobilisation**	**Tooth abrasion**	**Starvation/ dehydration**	**Gastro-intestinal blockages**	**Fluorosis**	**Loss Causes**	**Vegetation losses (%)**	**Vegetation loss cause**
A	✓	-	✓	-	✓	✓(chronic)	Starvation and lack of clean water.	25	Burial
B	✓(on-going)	-	✓	-	✓	✓(chronic)	Evacuated animals as soon as possible. Killed some for household use.	25	Burial and remobilisation
C	✓(on-going)	-	✓	✓	✓	✓(chronic)	Starvation (no spring grass), dehydration (stream dried up) and rumen blockages. Tooth abrasion. 6-year drought compounded problems. No autopsies.	50	Burial and remobilisation
D	✓(on-going)	-	✓	✓	✓	✓(chronic)	Remobilisation issues. Also experienced losses from 1960 CC-VC tephra fall due to stomach blockages	25	Burial and remobilisation
E	✓(on-going)	-	✓	✓	✓	✓(chronic)	Tephra in rumen causing stomach blockages. Tooth abrasion. Issues with water supply.	25	Burial and remobilisation

When estimating agricultural losses due to the 2011 CC-VC tephra fall using DDS (Jenkins et al. 2014) and impact thresholds (Wilson et al. 2009), the national park region performed much better than expected given the large thicknesses received (>300 mm). This is demonstrated by both current schemes (Fig. 2.5 a & b) and the two older scales (Neild 1998 & Blong 1984; Fig. 2.5 c & d), as based on thicknesses damage should have been much more severe, with decades of recovery and retiring of land predicted (Table 2.5; Fig. 2.5). The more positive outcome may be due to the unique style of farming in the area, where animals are free to roam large distances of parkland at low stocking rates and are used to foraging for food where possible. Vegetation recovery was also more rapid compared to recovery in the semi-arid area, due to the high levels of rainfall and the temperate climate being favourable to tephra weathering and incorporation into the soil (Shoji et al. 1993). The performance of both livestock and vegetation means that the existing DDS and hazard intensity thresholds do not correspond well with the scenario faced in the national park region.

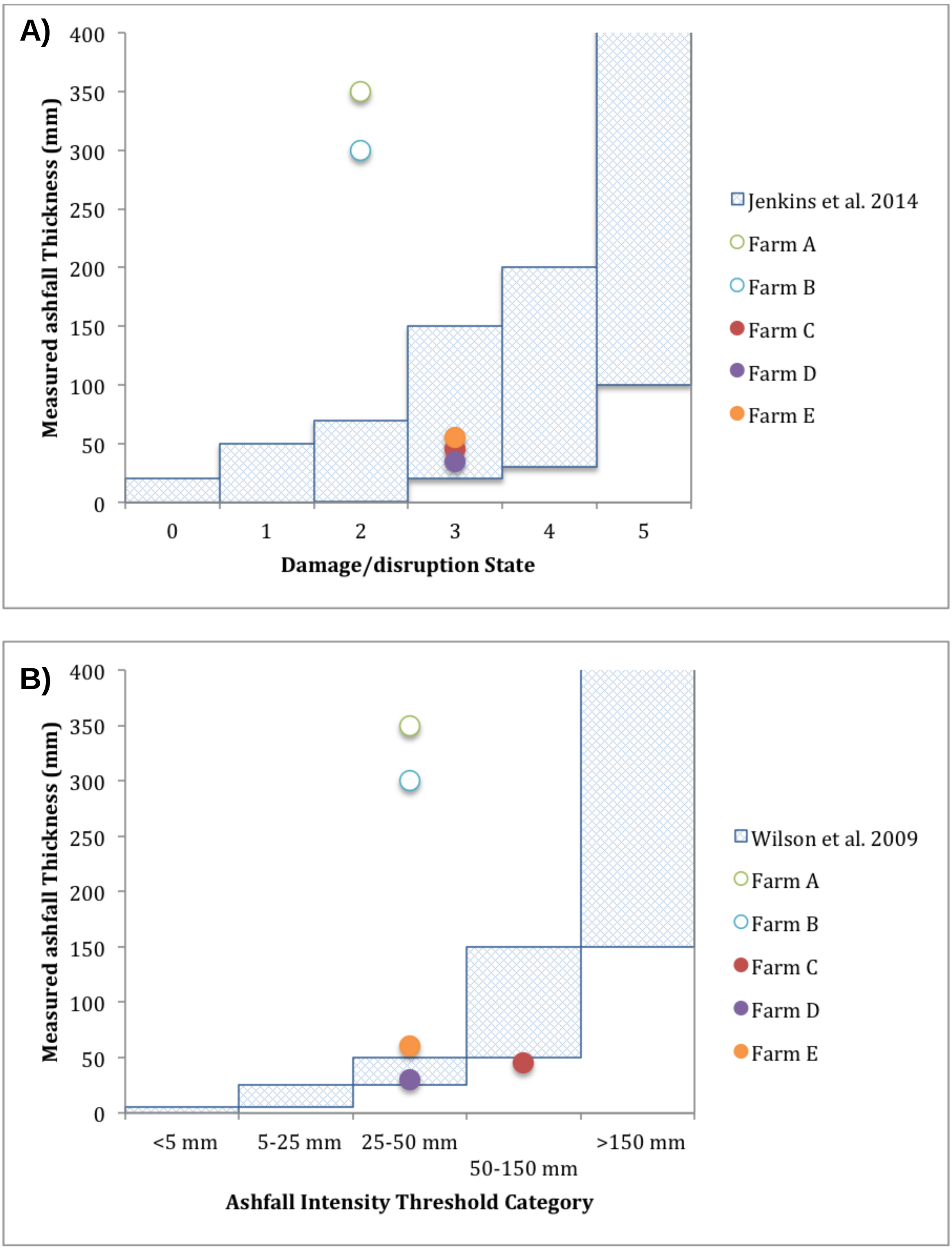
In contrast, the scales correlate well with the agricultural impacts and hazard intensities faced in the steppe region (Table 2.5; Fig. 2.5). This is unexpected due to the extreme climatic conditions faced. Farming conditions prior to the eruption were already marginal, with farmers often having to purchase supplementary feed due to drought conditions. The area also faced an extreme amount of wind remobilisation, where months after the tephra fall event animals still needed to be sheltered during windy conditions. These conditions are not typical of what would occur after tephra fall events in other volcanically active countries with more productive agricultural settings (e.g., New Zealand, Japan, Indonesia, etc.). Therefore as DDS scales correlate well with losses in the steppe it is unlikely that the scales would be good indicators of impacts in more agriculturally favourable conditions.

Table 2.5: Comparison of CC-VC tephra fall impacts to interviewed farms with existing damage state scales.

Farm ID	Tephra thick-ness (mm)	Damage State based on thickness (Wilson et al. 2009)#	Damage state description	Damage state based on observations	Justification of assigned damage state	Damage state based on thickness (Jenkins et al. 2014)	Damage state description	Damage state based on observations	Justification of assigned damage state
A	300+	>150mm category	New soil formation needs to occur (up to decades)	25-150 category	Tephra was incorporated into soil within months	5	Major rehabilitation required/ retirement of land	2	No land was retired and very little rehabilitation work was undertaken
B	300+	>150mm category	New soil formation needs to occur (up to decades)	25-150 category	Tephra was incorporated into soil within months	5	Major rehabilitation required/ retirement of land	2	No land was retired and very little rehabilitation work was undertaken
C	50	25-150 category	Integration of tephra into soil in 1-5 years	50-150 mm category	Recovery will be limited within the next growing season	2-3	Minor to major productivity loss (remediation required)	3	Losses were >50% across the region, however due to lack of resources very little remediation took place
D	30-45	25-150 category	Integration of tephra into soil in 1-5 years	25-150 category	Forecast time to total recovery (~5 years) is within what is predicted	2-3	Minor to major productivity loss (remediation required)	3	Losses were >50% across the region, however due to lack of resources very little remediation took place
E	50	25-150 category	Integration of tephra into soil in 1-5 years	25-150 category	Forecast time to total recovery (~5 years) is expected	2-3	Minor to major productivity loss	3	Losses were >50% across the region, however due to lack of resources very little remediation

Affected area	**Tephra thick-ness (mm)**	**Damage State based on thickness (Wilson et al. 2009)#**	**Damage state description**	**Damage state based on observations**	**Justification of assigned damage state**	**Damage state based on thickness (Jenkins et al. 2014)**	**Damage state description**	**Damage state based on observations**	**Justification of assigned damage state**
Nahuel Huapi National Park	250-400	>150mm category	New soil formation needs to occur (up to decades)	25-150 category	Whilst tephra did need to be incorporated into soil this occurred over months rather than years/decades	5	Major rehabilitation required/retirement of land	2	No land was retired and very little rehabilitation work was undertaken (due in part to it being a national park)
Steppe Region (incl. Jacobacci)	40-60	25-150 category	Up to 5 years recovery time	25-150 category	~	2-3	Minor to major productivity loss (remediation required)	3	Losses were >50% across the region, however due to lack of resources very little remediation took place

Not suggested as true damage states, rather guidelines for what impacts to expect.


A)
Measured ashfall Thickness (mm)
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
Damage/disruption State
Jenkins et al. 2014
Farm A
Farm B
Farm C
Farm D
Farm E
B)
Measured ashfall Thickness (mm)
400
350
300
250
200
150
100
50
0
<5 mm
5-25 mm
25-50 mm
50-150 mm
>150 mm
Ashfall Intensity Threshold Category
Wilson et al. 2009
Farm A
Farm B
Farm C
Farm D
Farm E

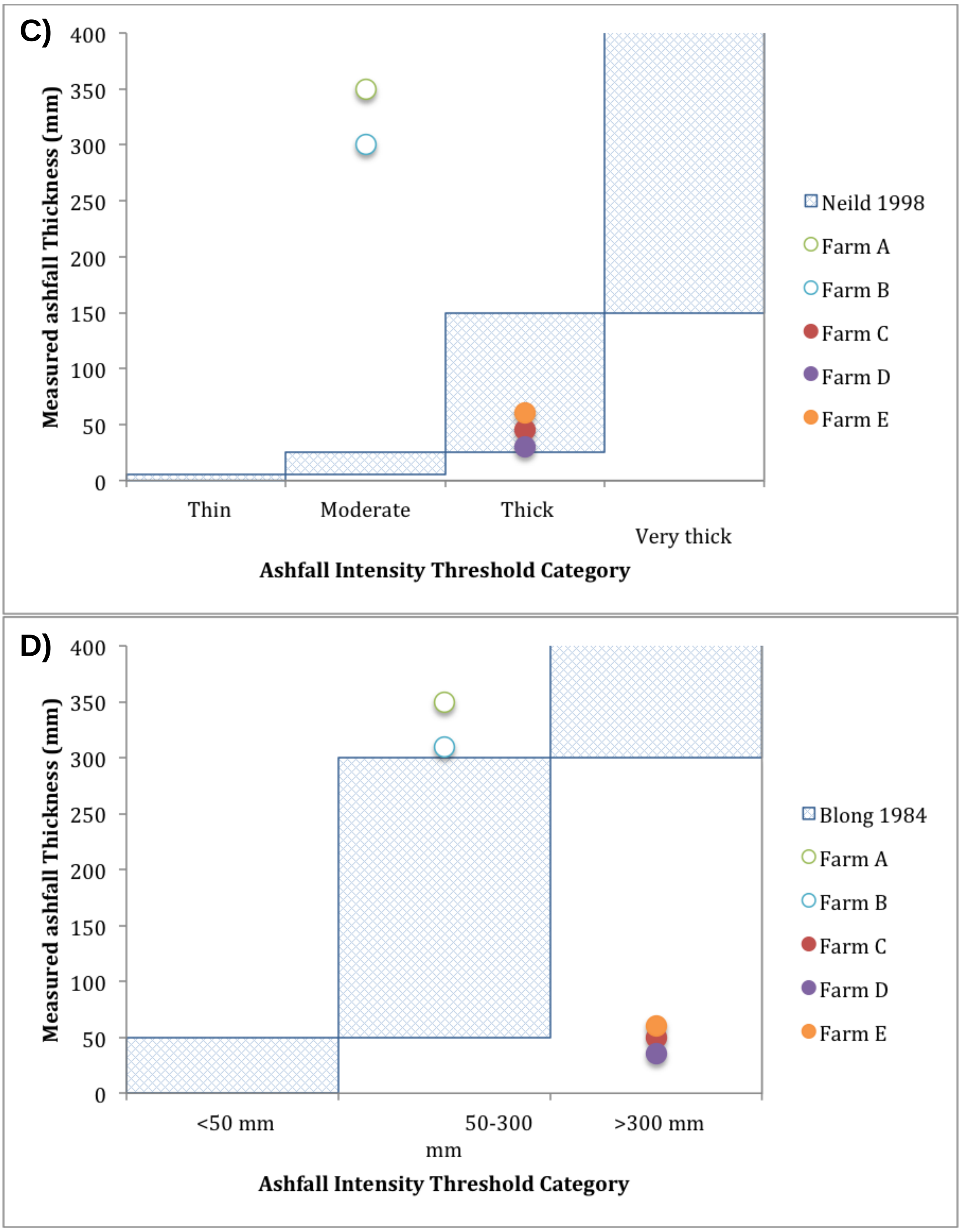


Figure 2.5: Graphs showing the thicknesses of tephra received compared to the damage/disruption states that the farms were within based on descriptions, for four different schemes (A) Jenkins et al. 2014; B) Wilson et al. 2009; C) Neild 1998; D) Blong 1984). Hollow points show farms within the Nahuel Huapi National Park where extensive, prolonged wind remobilisation did not occur.

2.4.2 Critical infrastructure

2.4.2.1 Electrical systems

The tephra fall caused widespread disruption of electricity supplies in the study area. As observed for other eruptions with similar urban tephra fall thicknesses (Table 2.6), the effect of tephra contamination on distribution lines and substation insulators, was induced leakage currents, insulator flashover, and the blockage of air intakes at thermal oil and coal fired generation plants (Wardman et al. 2012). In addition, continual tripping of switches due to flashover events, combined with the presence of fine tephra in switches, led to abrasion of the metallic conductors that reduced the contact between electrodes, reducing their functionality. This required ongoing replacement of the switches, particularly in the Jacobacci area (Fig. 2.6; Table 2.7). Thermal generation facilities also suffered significant disruption in both Bariloche and Villa La Angostura, mainly due to tephra blockage of air intakes (Table 2.7).

Figure 2.6: A) Outdoor grid exit point substation for Bariloche; B) 20 MW diesel generation plant installed to help with power cuts after the tephra fall; C) Grid exit point substation near Jacobacci.

The most commonly employed mitigation measure across the three main centres was to spray insulators and lines with high-pressure hoses. This was effective in the short term but further tephra falls or wind remobilisation would require the cleaning to be undertaken again. Increasing the length of insulator pins in Villa la Angostura was trialled and proven to be effective at preventing tephra fall-induced flashover. This resulted in all pins in the town eventually being upgraded, which has increased the network's resilience to future events (Table 2.8). Management of the power cuts in Bariloche included the development of a 20 MW diesel generation plant (Fig. 2.6 b; Table 2.8), however this did not cover the full 45-55 MW requirements and experienced problems with air intakes becoming clogged with tephra (Table 2.7).

Table 2.6: Tephra thicknesses with impacts compared to previous tephra fall events (NI - Not investigated within studies; NA- Not applicable).

<table>
<tr><th colspan="2">Eruption</th><th colspan="5">CC-VC 2011</th><th>Tongariro 2012</th><th colspan="2">Shinmoedake 2011</th><th>Sakurajima 2011</th><th>Tungurahura 2010</th></tr>
<tr><th colspan="2">Localities impacted</th><th colspan="2">Villa la Angostura</th><th colspan="2">Bariloche</th><th>Jacobacci</th><th>Rangipo</th><th>Kirishima City</th><th>Miike</th><th>Kagoshima</th><th>Riobamba</th></tr>
<tr><td colspan="2">Tephra thicknesses (mm)</td><td colspan="2">150-170</td><td colspan="2">30-45</td><td>50</td><td>2</td><td>1</td><td>60-80</td><td>1</td><td>10</td></tr>
<tr><td rowspan="5">Electricity</td><td>Flashover</td><td colspan="2">✓</td><td colspan="2">✓</td><td>✓</td><td>✓</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Air intakes clogging</td><td colspan="2">✓</td><td colspan="2">✓</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Switch abrasion</td><td colspan="2"></td><td colspan="2"></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Controlled outage</td><td colspan="2"></td><td colspan="2"></td><td></td><td></td><td></td><td>✓</td><td></td><td>✓</td></tr>
<tr><td>Generator blockage</td><td colspan="2"></td><td colspan="2"></td><td>✓</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="6">Water</td><td></td><td>Stream-fed</td><td>Main WTP</td><td>Stream-fed</td><td>Main WTP</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Turbidity increase</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td></td><td>✓</td><td>NI</td><td>NI</td><td>NI</td><td></td></tr>
<tr><td>Damage to pumps</td><td></td><td>✓</td><td>✓</td><td>✓</td><td></td><td></td><td>NI</td><td>NI</td><td>NI</td><td></td></tr>
<tr><td>Filtration contamination</td><td>✓</td><td></td><td></td><td>✓</td><td></td><td></td><td>NI</td><td>NI</td><td>NI</td><td></td></tr>
<tr><td>Clogging of filters</td><td>✓</td><td>✓</td><td>✓</td><td></td><td></td><td></td><td>NI</td><td>NI</td><td>NI</td><td></td></tr>
<tr><td>Increased demand</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td></td><td>NI</td><td>NI</td><td>NI</td><td></td></tr>
<tr><td rowspan="4">Waste water</td><td>Effects on sewer networks (clogging, wear on pumps)</td><td colspan="2">NA</td><td colspan="2">✓</td><td>NA</td><td>NI</td><td>NI</td><td>NI</td><td>NI</td><td>NI</td></tr>
<tr><td>Damage to pre-screening equipment</td><td colspan="2">NA</td><td colspan="2">✓</td><td>NA</td><td>NI</td><td>NI</td><td>NI</td><td>NI</td><td>NI</td></tr>
<tr><td>Power outages affecting pumping</td><td colspan="2">NA</td><td colspan="2">✓</td><td>NA</td><td>NI</td><td>NI</td><td>NI</td><td>NI</td><td>NI</td></tr>
<tr><td>Tephra accumulation in treatment tanks</td><td colspan="2">NA</td><td colspan="2">✓</td><td>NA</td><td>NI</td><td>NI</td><td>NI</td><td>NI</td><td>NI</td></tr>
<tr><td rowspan="5">Roading</td><td>Road closures</td><td colspan="2">✓</td><td colspan="2">✓</td><td>✓</td><td>✓</td><td></td><td>✓</td><td></td><td></td></tr>
<tr><td>Air filter blockage</td><td colspan="2">✓</td><td colspan="2"></td><td>✓</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Decreased traction</td><td colspan="2">✓</td><td colspan="2">✓</td><td>✓</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Decreased visibility</td><td colspan="2">✓</td><td colspan="2"></td><td>✓</td><td></td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>Road markings covered</td><td colspan="2">✓</td><td colspan="2">✓</td><td>NA</td><td>✓</td><td>✓</td><td></td><td>✓</td><td></td></tr>
<tr><td>Airport</td><td>Airport closed</td><td colspan="2">NA</td><td colspan="2">✓</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>✓</td><td>✓</td></tr>
</table>

Eruption		**Pacaya 2010**	**Chaiten 2008**		**Ruapehu 1995/96**	**Rabaul 1994**	**Mt Spurr 1992**	**Hudson 1991**		**St Helens 1980**
Localities impacted		**Guatemala City**	**Futaleufu**	**Esquel**	**Gisborne**	**Rabaul**	**Anchorage**	**Perito Moreno**	**Los Antiguos**	**Yakima**
Tephra thicknesses (mm)		20-30	80	15	3	600-1000	3-5	30-40	75	6-10
Electricity	Flashover	✓	✓	✓	✓	NI	NI			✓
	Air intakes clogging					NI	NI			
	Switch abrasion					NI	NI			
	Controlled outage	✓				NI	NI			
	Generator blockage		✓			NI	NI			
Water	Turbidity increase	✓	✓	✓	✓	NI	✓	✓	✓	✓
	Damage to pumps	✓		✓		NI		✓		
	Filtration contamination					NI	✓			
	Clogging of filters		✓			NI	✓		✓	
	Increased demand		✓	✓		NI				✓
Waste water	Effects on sewer network (clogging, wear)	✓				NI	✓	NI	NI	✓
	Damage to pre-screening equipment	✓				NI		NI	NI	✓
	Power outages affecting pumping	✓				NI		NI	NI	✓
	Tephra accumulation in treatment tanks	✓				NI		NI	NI	✓
Roading	Road closures		✓	✓	✓	✓		✓	✓	✓
	Air filter blockage		✓	✓						
	Decreased traction		✓	✓	✓	✓		✓	✓	✓
	Decreased visibility		✓	✓	✓	✓	✓	✓	✓	✓
	Road markings covered		✓	✓		✓				✓
Airport	Airport closed	✓	NA	NI	✓	✓	✓	NA	NA	✓

Table 2.7: Summary of system design and impacts for infrastructure after the 2011 CC-VC eruption.

Infrastructure	Towns	Design	Impacts	Main issues
Electricity	Villa la Angostura	Not connected to national grid; 6.1MW thermal generation plant	Flashover on 13.2 kV, 380 V, and 220 V networks due to damp tephra fall; Dry tephra fall clogged air intakes for the thermal plant resulting in precautionary shutdowns	**Flashover; air intake clogging**
	Bariloche	Single transmission line and one grid exit point from national grid; Outdoor GXP substation	Whole town lost power for 8 hours, with some not reinstated for 24 hours after the initial tephra fall; power cuts due to GXP substation suffering flashover due to tephra; contamination of switches and busbars; diesel and gas generators were deployed around the town but the air intakes became blocked with tephra	**Flashover; air intake clogging; switch abrasion; generator blockage**
	Jacobacci	Single transmission line and one grid exit point from national grid; Outdoor GXP substation	Some flashover caused intermittent power cuts to the town (usually for only a few hours); Tripping of switches due to flashover and abrasion of metallic components	**Flashover; switch abrasion**
Water Supply	Villa la Angostura central system	Town centre supplied by Lomas del Correntoso treatment system. Water is extracted from Lago Correntoso and Lago Nahuel Huapi then pumped up an 80 m rise to the WTP. An initial filtration step is followed by pressure sand filtration then chlorination then gravity fed to households.	The eruption increased the level of suspended tephra in the lake, which caused high levels of wear and tear on pumping equipment. Power outages also caused problems for this system.	**Turbidity increase; damage to pumping equipment**
	Villa la Angostura peripheral systems	A range of smaller systems based on intakes from streams or the lake. Systems are generally gravity-fed. System designs vary considerably, but in general the stream-fed systems are poorly maintained and do not achieve a good level of sediment removal prior to chlorine dosing. Water supplied to households may not contain adequate chlorine residuals.	Stream-fed systems were severely affected by the eruption, with intake structures inundated with tephra. These systems continued to experience problems in rainy conditions when further tephra was washed downstream. Some systems have been abandoned.	**Damage to intake structures; turbidity increase; other contamination of raw water source; clogging of filters; overall system failure**

Infrastructure	Towns	Design	Impacts	Main issues
Water (cont.)	Bariloche central system	Bariloche's central water treatment plant has an intake in Lago Nahuel Huapi. Water is pumped up a 150 rise to storage tanks. The treatment process does not include a preliminary coagulation/flocculation step as intake water is normally very low in turbidity (0.2-0.4 NTU). Filtration is through open-air slow sand filters prior to chlorination.	The eruption increased the level of suspended tephra in the lake, which not only caused accelerated wear and tear on pumping equipment but also allowed tephra to enter the treatment plant (both via the intake and by direct fallout) where it clogged open sand filter beds. A greatly increased level of maintenance was required to manage these problems and remain in production. A city-wide power outage caused an interruption to water production.	**Turbidity increase; damage to pumping equipment; clogging of filters**
	Bariloche peripheral systems	Similar to range of smaller systems in Villa la Angostura; outlying neighbourhoods supplied by smaller systems with intakes from springs, streams and the lake, with wide variety of treatment system design.	Effects were similar to, though less severe than, for Villa la Angostura.	**Damage to intake structures; turbidity increase; clogging of filters**
	Jacobacci	17 groundwater wells with well-head pumps enclosed in pumphouses; water then chlorinated and distributed	This system is completely enclosed and thus proved resilient to the tephra fall. However problems were experienced with high water demand as the town was repeatedly subjected to wind-remobilised tephra and additional water was required for clean up	**A sustained increased water demand**
	Villa la Angostura	Not investigated during field visit		-
Waste water	Bariloche	Treatment plant 4.3 km east of the city; pumped to plant then screened through 25 mm bars, pumped through a decanter, then through an anaerobic tank before entering the biological reactor (*Nocardia spp*. Bacteria), finally wastewater sludge is separated and taken to the dewatering plant	Solids coming into the plant increased from 4500 mg/L to 8000 mg/L in the 3 days after the eruption due to tephra contamination; sewer lines and storm drains were meant to be separated but sometimes illegally connected which meant large volumes of tephra entered the system; power cuts meant that pumping stations without generators stopped; pump impellers had accelerated wear; 1 m of tephra accumulated in the bottom of the 4.5 m deep biological reactor which reduced the plants capacity	**Blockages of stormwater catchpits and sewer lines and junctions; accelerated wear and tear to sewage pump impellers; power outages affected pumping**
	Jacobacci	Not investigated during field visit		-

Infrastructure	Towns	Design	Impacts	Main issues
Roading	Villa la Angostura	Asphalt main roads, unsealed secondary routes	Route 231 (asphalt) connecting Villa la Angostura with Bariloche was closed after the eruption for a day, then reopened but with speed restrictions; the Samore Pass border between Chile and Argentina was closed for several weeks after the eruption due to the thickness of tephra recieved (>300 mm); drivers reported a loss of traction, inability to see road markings, and some issues with air filters becoming clogged	**Road closures; road markings not visable; loss of traction; air filter clogging**
	Bariloche	Asphalt	Route 40 (asphalt) the main road into Patagonia was closed for two days after the eruption; main road within the town were covered with 50 mm of tephra therefore authorities recommended that cars stayed off the road	**Road closures; road markings not visable; loss of traction; air filter clogging**
	Jacobacci	Predominantly unsealed	Visibility an issue due to wind remobilisation, this prevented almost all driving and clean up for the first week; road between Jacobacci and Bariloche closed for a few days, then reopened to limited traffic at low speeds	**Road closures; low visibility; road markings not visable; loss of traction; air filter clogging**
Airports	Bariloche	Fourth largest airport in Argentina; located 13 km outside of Bariloche; airport land covers 1,810 Ha with a 2,400 m runway	Airport was closed for a month due to tephra fall; approximately 1000 tonnes of tephra was deposited onto airport land; when the airport reopened some airlines (LAN Chile and Aerolinas Argentina) did not recommence flights due to fears around tephra fall and accurate forecasting; full service resumed on 20 December 2011	**Airport closure; airlines reluctant to resume flights**

Table 2.8: Pre-event and post-event mitigation strageties for critical infrastructure sectors in the three main urban areas affected by tephra fall.

Infrastructure	Towns	Pre-event planning	Mitigation	Recovery strategies
Electricity	Villa la Angostura	Some tephra fall planning, mosly around the cleaning of lines	Fire trucks deployed to wash insulators; Increased insulator pin length from 250 mm to 500 mm (initially in locations prone to flashover, but eventually all 3,500 insulators were changed)	**Cleaning insulators; increase insulator pin length**
	Bariloche	Some tephra fall planning, mostly around the cleaning of lines	20 MW diesel generation plant installed for back-up supply (usual demand 45-55 MW so some shortfall); fire crews rinsed insulators	**Cleaning insulators; generator use**
	Jacobacci	No tephra fall specific planning	Switches required ongoing replacements (for months after the eruption); volunteer firefighters washed lines after the eruption and severe remobilisation events (however due to tephra remaining dry because of the lack of rainfall flashover risk was reduced)	**Cleaning insulators; replacement of switches**
Water Supply	Villa la Angostura	Planning for stream blockages (army brought in to clear these)	Drilled a groundwater well ~21 m deep (not treated and distributed via gravity fed system) to make up for the short fall due to issues with stream blockages and pump maintenance issues; pumps that were abraided by tephra fall were replaced	**Replacement of pumps/pump components; new groundwater well drilled**
	Bariloche	No tephra fall specific planning	Sand filters neded to be cleaned more frequently than the pre-eruption routine which was for one sand bed out of rotation for cleaning every ten days; generators prioritised for running pumps to treatment plant, however the demand (2 MW) exceeded the capacity of the generator trucks (1 MW per truck)	**Replacement of pumps/pump components; cleaning of filtration mechanisms**
	Jacobacci	No tephra fall specific planning	A new well was dug to to cover the increased demand due to the eruption	**New groundwater well drilled**

Infrastructure	Towns	Pre-event planning	Mitigation	Recovery strategies
Waste water	Villa la Angostura	No tephra fall specific planning	-	**-**
	Bariloche	Some planning but only to try prevent tephra from getting into system initially	Some discharge of untreated wastewater was made into the lake as the system became overwhelmed; municipal crews dug tephra out of catchpits to try prevent tephra getting into the system; manually moved generators around the system to keep wastewater moving; pump impellers replaced every six months rather than 12	**Discharge of untreated wastewater into lake; replacement of pump components**
	Jacobacci	No tephra fall specific planning	-	**-**
Roading	Villa la Angostura	Some tephra fall planning but underestimated the amount of tephra fall and the number of trucks required	Route 231 and the main roads within the town were cleared by bulldozers the day after the eruption; water tankers were used to dampen down tephra and prevent remobilisation	**Bulldozing and sweeping roads clear; dampening down tephra; cleaning air filters more frequently**
	Bariloche	Some tephra fall planning but underestimated the amount of tephra fall and the number of trucks required	Main roads began to be cleared of tephra by municipal authorities within hours of eruption; road sweepers were deployed for smaller tephra fall events	**Bulldozing and sweeping roads clear; dampening down tephra; cleaning air filters more frequently**
	Jacobacci	Some tephra fall planning, but not specific amounts and equipment	Speeds reduced to 20 km/hour on days where tephra fall was being remobilised; municipal water trucks dampened down tephra on roads; tephra removal and clean up focussed on main roads and reopening link to Bariloche	**Bulldozing and sweeping roads clear; dampening down tephra; cleaning air filters more frequently**
Airports	Bariloche	Some tephra fall planning	Did not receive official warning so no prior actions could be taken; tephra fall was placed into hollows and dips in the surrounding land and then vegetated to prevent remobilisation; an extensive irrigation system was also installed to keep tephra from remobilised onto the runway	**Removal of tephra; dampening down of tephra; permanent irrigation system installed**

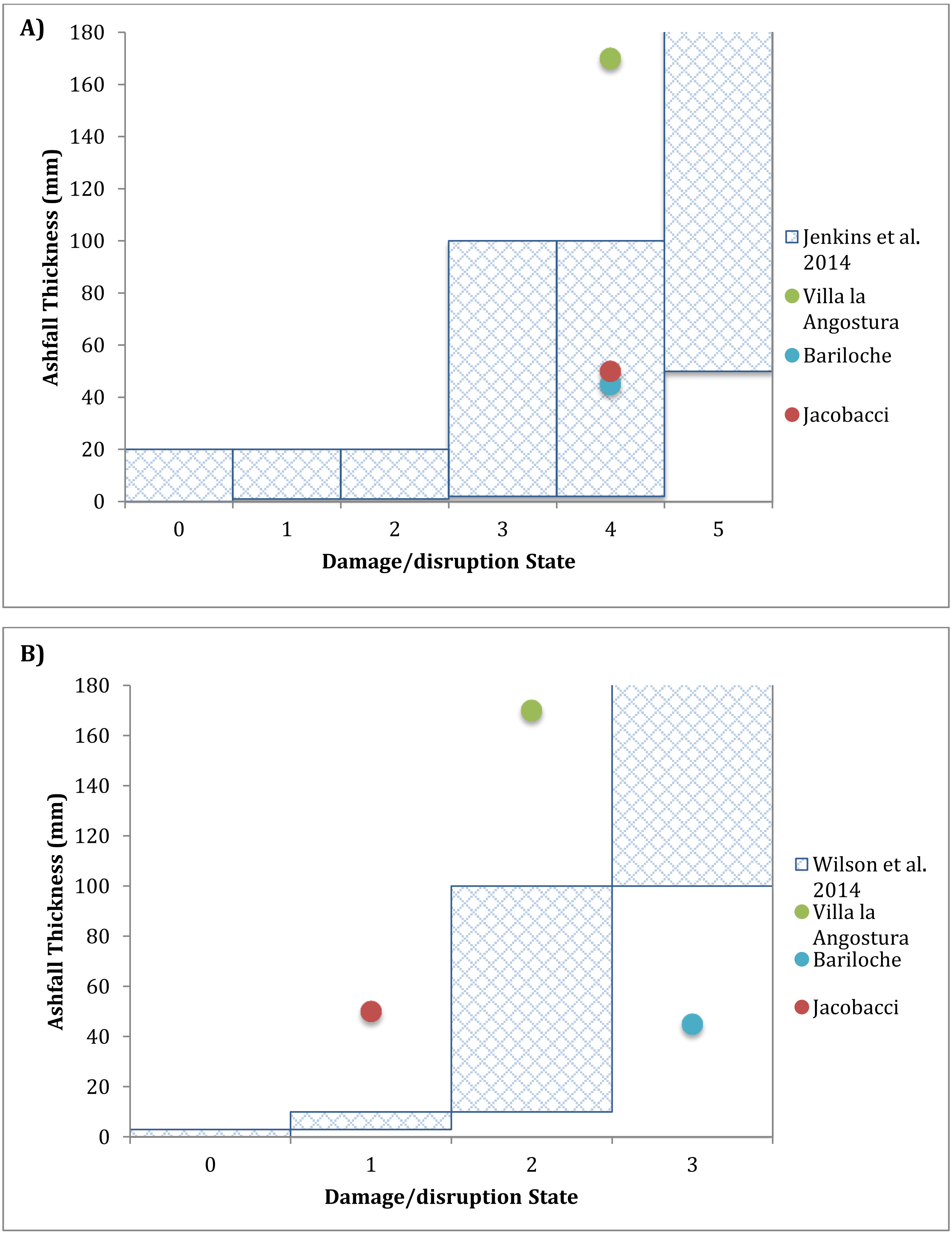


Figure 2.7: Observed damage states for the electricity network across the three main urban centres, compared to hazard intensity ranges given with the A) Jenkins et al. 2014 and B) Wilson et al. 2014 damage state schemes.

DDS were assigned to the electricity network impacts for Villa la Angostura, Bariloche, and Jacobacci. The disruption experienced in Villa la Angostura was less severe than predicted by DDS, and there were no components seriously damaged or line breakages in Bariloche as the Wilson et al. (2014) DDS suggested may occur (Table 2.9; Fig. 2.7). DDS descriptions assigned based on tephra thicknesses were accurate for Jacobacci, despite the fact that most damage occurred due to wind remobilisation abrading components. Severe wind remobilisation, such as that which occurred on the semi-arid steppe, is not usually experienced in temperate environments, which again could possibly suggest that the DDS hazard thresholds would not work in all climatic scenarios.

2.4.2.2 Water supply

Villa la Angostura

In Villa la Angostura, the town centre is supplied by a relatively advanced treatment system. From dual intakes on Lago Correntoso and Lago Nahuel Huapi, water is pumped 80 m uphill to a treatment plant where there is an initial filtration step followed by pressure sand filtration then chlorination (Fig. 2.8). The eruption increased the level of tephra suspended in the lakes, which caused high levels of wear and tear on pumping equipment. For instance, one pump had been in service since 1997 with no problems, but had to be completely replaced after the eruption. Power outages also caused problems for this system, which relies on pumping, and generators were brought in to maintain pumping.

Outlying neighbourhoods are served by a range of smaller and more rudimentary systems with intakes either in the lakes or in streams, followed by initial passage through flow control/settling basins then treatment via slow sand filter beds followed by chlorine dosing. These systems are in general poorly maintained, and residual chlorine levels in the distribution system are inadequate for effective disinfection. Stream-fed systems were severely affected by the eruption; with intake structures inundated with tephra and had to be cleared out manually. These systems continued to experience problems in rainy conditions, with further mobilisation of tephra deposited in the catchment. To meet demand at the time, water was distributed by the Army to affected neighbourhoods in 1000-litre tanks, along with pallets of bottled drinking water. To meet continuing demand, a new 21-metre deep well was excavated.

Bariloche

The Bariloche water treatment plant (WTP) provides around 80% of the city's water supply, with outlying neighbourhoods supplied by a range of smaller systems with intakes from springs, streams and Lago Nahuel Huapi (Table 2.7). Effects of the eruption on these smaller systems were similar to those described for Villa la Angostura and are not described again here.

The centralised WTP has an intake in Lago Nahuel Huapi with electrical pumping of water up a 150 m rise to storage tanks. As the turbidity in the lake is almost always very low (0.2-0.4 NTU), the treatment train does not include an initial coagulation/flocculation step prior to filtration. Following the eruption, turbidity in the lake increased to an unprecedented 26 NTU. Suspended tephra entered the treatment system through the intake pipes and via direct fallout, and caused a range of problems. Pumps suffered accelerated wear and tear, with impellers suffering three years' wear in six months. Tephra also entered the drive shaft assembly above a pump motor, and caused it to become unbalanced and put additional load on the motor. Tephra also contaminated the open-air sand filter beds (Fig. 2.9). In general, all these problems were manageable, but a greatly increased level of maintenance was required. The only interruption to production was when a city-wide power outage of 12 hours duration occurred, and for the first time in twenty years, no water was supplied to central Bariloche.

Table 2.9: Comparison of CC-VC tephra fall impacts to infrastructure with existing damage state scales.

Infrastructure	**Town**	**Tephra thick-ness (mm)**	**Damage State from thickness (G.Wilson et al. 2014)**	**Damage state description**	**DS based on obser-vations**	**Justification of assigned damage state**	**DS from thickness (Jenkins et al. 2014)**	**Damage state description**	**DS based on obser-vations**	**Justification of assigned damage state**
Electricity	Villa la Angostura	150-170	3	Damage: structural damage to transmission equipment; Distruption: widespread disruption to supply with some permanent issues	2	No reported issues with structural damage, no permanent disruption	5	Damage: structural damage; Function: permanent disruption	3-4	No reported issues with structural damage, no permanent disruption
	Bariloche	30-45	2	Damage: damage to exposed moving parts, possible line breakages; Disruption: flashover, cleaning and repair	1	No damage reported to lines or parts	3-4	Damage: some damage to components; Function: disruption requiring repair	3-4	~
	Jacobacci	50	2		2	~	3-4		3-4	~
Water Supply	Villa la Angostura	150-170	3	Damage: infilling of open reservoirs and tanks, collapse of reservoir roofs; Disruption: severe contamination of water supply and exhaustion of supply due to demand	2	No roof collapse reported, water demand raised but not exhaused	Not included in damage states due to issues with relating impacts to a single hazard intensity measure (in this case tephra thickness (mm)			
	Bariloche	30-45	2	Damage: damage to pumping equipment, infilling of tanks; Disruption: contamination of water	2	~				
	Jacobacci	50	2		0	No damage due to pumps being in pumphouses				

Infrastructure	**Town**	**Tephra thick-ness (mm)**	**Damage State from thickness (G. Wilson et al. 2014)**	**Damage state description**	**DS based on obser-vations**	**Justification of assigned damage state**	**Damage state from thickness (Jenkins et al. 2014)**	**Damage state description**	**Damage state based on obser-vations**	**Justification of assigned damage state**
Waste water	Villa la Angostura	150-170	3	NA	NA	NA	Not included in damage states due to issues with relating impacts to a single hazard intensity measure (in this case tephra thickness (mm)			
	Bariloche	30-45	2	Damage: sedimentation causing some blockages and damage, possible infilling of tanks; Disruption: temporary disruption to clean network, possible release of untreated sewage	2	~				
	Jacobacci	50	2	NA	NA	NA				
Roading	Villa la Angostura	150-170	3	Damage: complete burial, structural damage to bridges; Disruption: roads impassable, widespread closures	2	No structural damage reported, some vehicles could use roads at limited speeds	4	Damage: road surface abrasion; Function: 4WDs obstructed	4	~
	Bariloche	30-45	1	Damage: possible abrasion of road markings and paved surfaces; Disruption: reduced visibility and traction	1	~	3	Damage: road surface and marking abrasion; Function: 2WD vehicles obstructed	2	Some vehicles could use roads at very limited speeds
	Jacobacci	50	2	Damage: possible abrasion of road markings and surfaces; Disruption: reduced traction, closures	2-3	Remobilisation of the tephra fall deposit meant that roads were impassable	3		3	~

Infrastructure	Town	Tephra thick-ness (mm)	Damage State from thickness (G. Wilson et al. 2014)	Damage state description	Damage state based on obser-vations	Justification of assigned damage state	Damage state from thickness (Jenkins et al. 2014)	Damage state description	Damage state based on obser-vations	Justification of assigned damage state
Airports	Bariloche	30-45	2	Damage: moderate abrasion of runway and landing lights; Disruption: airport closure	2	~	1-4	Damage: possible runway degradation; Function: runway closure	1-4	~

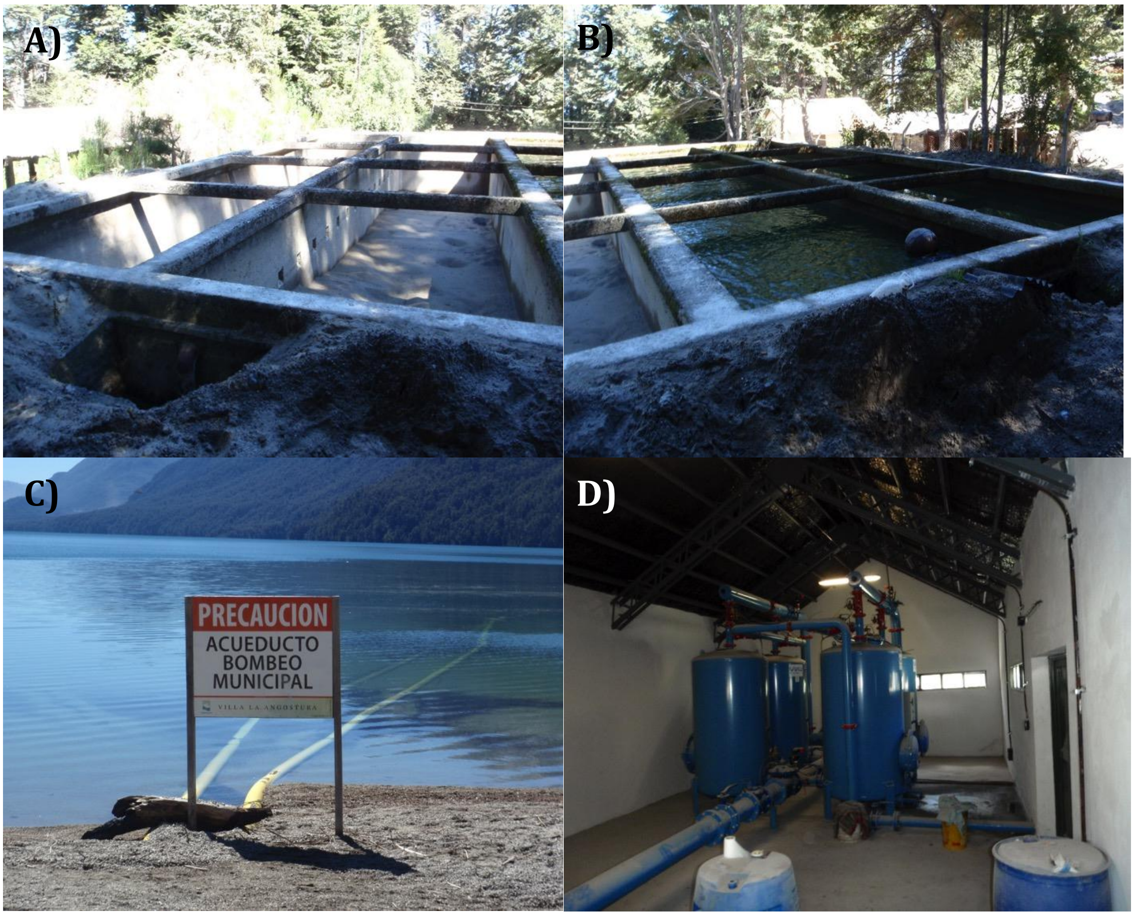


Figure 2.8: Villa la Angostura water supplies A) non-operational sand filters of the Las Piedritas stream-fed system, filled with tephra fall; B) operational sand filters at the Las Piedritas treatment site; C) Lomas del Correntoso intake from Lake Correntoso; D) Chlorination plant.

Jacobacci

In Jacobacci, the town’s water supply is based on extraction from a system of 17 groundwater wells. Wellhead pumps are enclosed in pump houses. The water is chlorinated then distributed to households. As the system is completely enclosed, the system proved resilient (Table 2.7 & 2.8). The main challenge was meeting water demand. Due to continued wind remobilisation and tephra redeposition, water demand would increase as the community cleaned up and dampened down tephra in the streets, from normal usage of 1 million L/day to as high as 3 million L/day.

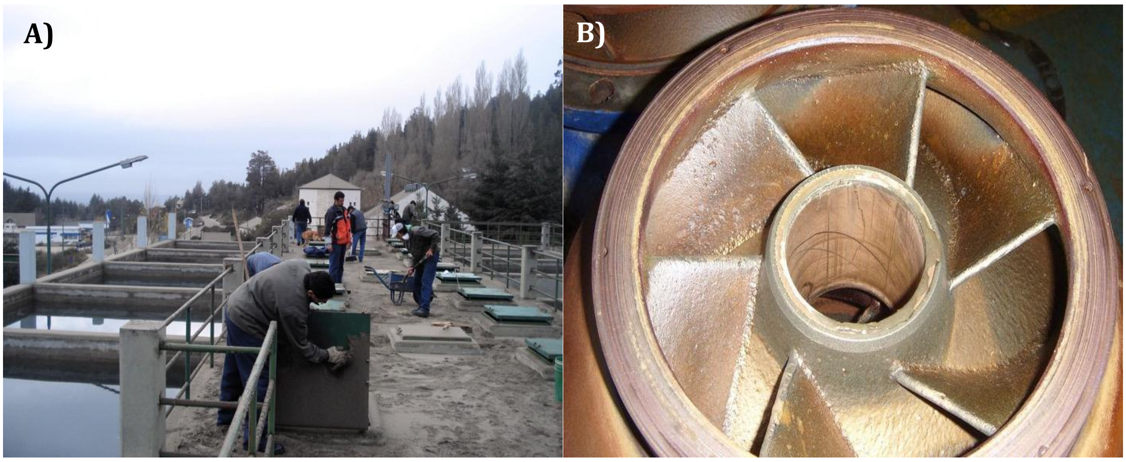


Figure 2.9: Bariloche water treatment plant A) people cleaning out open air sand filters after the tephra fall; B) pump impeller showing some accelerated abrasion due to tephra.

2.4.2.3 Role of system design

The critical importance of system design in determining resilience to tephra fall impacts is illustrated by comparing impacts on water supply systems in Bariloche (which received 30-45 mm tephra fall) and Jacobacci, which received 50 mm tephra fall initially and was also subjected to prolonged exposure to wind-remobilised tephra fall from upwind deposits (Table 2.6). At Jacobacci, the water supply system is based entirely on groundwater extraction, and as all parts of the system are enclosed, the system proved resilient to the tephra fall. However, the town did experience a sustained period of increased water demand after the eruption, which necessitated the excavation of a new well. In contrast, the city of Bariloche received a similar initial tephra fall. A water treatment plant that has a surface water intake and also has open-air sand filter beds supplies the central city. While the plant was able to maintain production (apart from an interruption caused by a 12-hour long power outage), a greatly increased level of maintenance of pumping equipment and the sand filter beds was required to manage problems caused by the presence of tephra in the treatment system.

Water supply systems were not included within the Jenkins et al. (2014) scheme due to difficulties in relating impacts to a single hazard intensity measure such as thickness. This highlights the difficulty in creating a standardised scale for water systems. The varied nature of multiple interconnected systems or many independent systems within the same catchment, both within a single urban area and when comparing between different towns, means that the creation of damage states for water systems is highly problematic. Jenkins et al. (2014), argues that these difficulties are insurmountable with current impact information, however G. Wilson et al. (2014) has attempted to create a scheme. The G. Wilson et al. (2014) damage states were applied to water supply systems for the three main urban centres; here we apply them only to the central water treatment plant in each of the towns, rather than the smaller peripheral treatment sites. This is due to the lack of detailed information at all of the smaller sites, and that the G. Wilson et al. (2014) scheme is better suited to larger centralised treatment plants.

Water supply systems in Villa la Angostura and Jacobacci both performed better than predicted, based on the application of the G. Wilson et al. (2014) DDS (Table 2.9; Fig 10). In Villa la Angostura there were no reports of roof collapse over treatment sheds, and whilst water demand was raised the supply was not exhausted, unlike what is suggested by the G. Wilson et al. 2014 DDS. This is likely due to the variety of water sources available preventing supplies being exhausted, that clean drinking water was trucked in, and possibly that the steep pitch of roofs (designed for yearly snowfalls) reduced adherence of tephra fall to roofs resulting in a decrease in the cleaning required. The DDS system applied was not designed to take into account the resilience of the Jacobacci completely covered supply system (Table 2.9; Fig. 2.10). This meant that there was no damage to equipment or tanks, and no issues with contamination of municipal supplies.

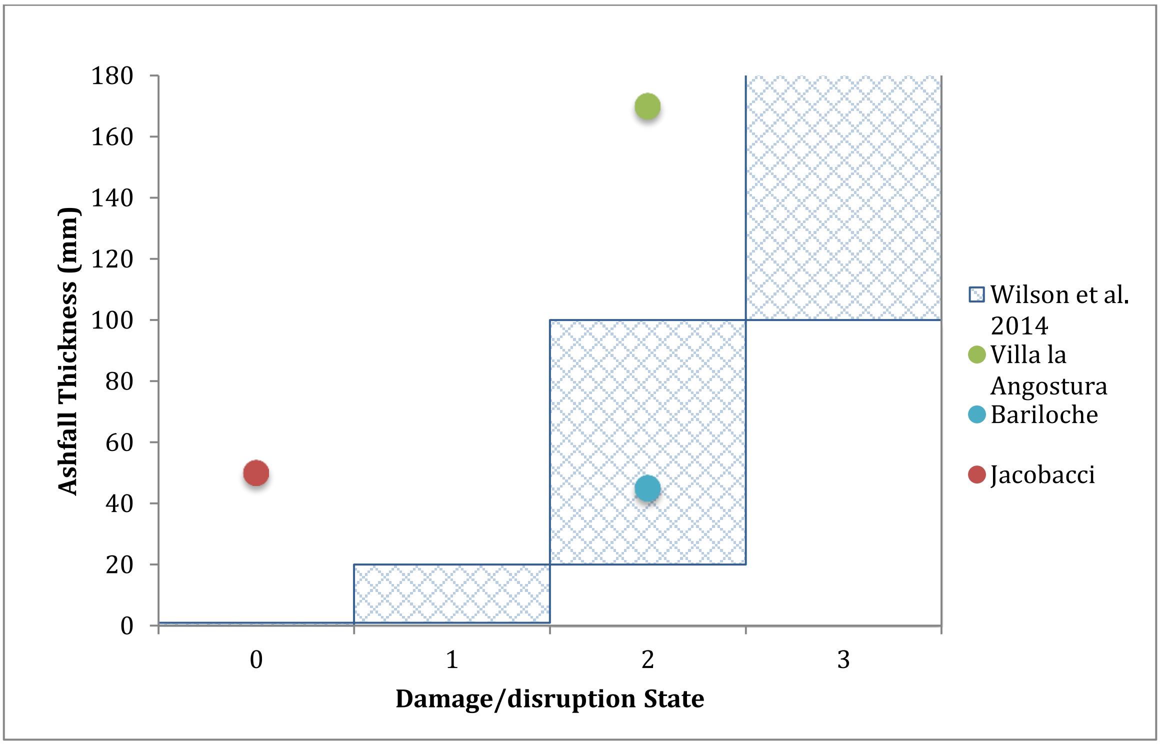


Figure 2.10: Observed damage states for the water supply network across the three main urban centres, compared to hazard intensity ranges given with the Wilson et al. 2014 damage state scheme.

2.4.2.4 Waste water systems

A centralised wastewater collection and treatment system serves the urban population of Bariloche which received 30-45 mm of tephra (Table 2.7; Fig. 2.11). While the sewer lines and storm water drains for the city are theoretically separate, there are in fact many illegal connections, and thus tephra entered both the stormwater and sewer networks despite barriers and sandbags being put in place in an attempt to exclude it. A further impact on the sewer network occurred on the 6/7 June 2011, when the city was affected by a widespread power outage related to the tephra fall. Not all pumping stations had emergency generators, although most had sufficient storage capacity to allow for six to eight hours of accumulation before overflows of raw sewage occur (Table 2.7). The situation was managed by manually moving emergency generators around between pumping stations (Table 2.8).

At the treatment plant, tephra accumulated in the biological reactor. This reactor is open-air; however most tephra entered the tank through the intake rather than from direct fallout. The reactor is 4.5 m deep, and the plant operator estimated that approximately 1 m of tephra had accumulated in the bottom. This did not interfere with the functioning of the microbial population in the pond, but did reduce the plant's capacity. The tephra caused few problems for the initial screening of wastewater (manual screening through static bars, followed by pumping up to a decanter for primary sedimentation.

No DDS were created for waste water in the Jenkins et al. (2014) study, as the complexity of waste water systems and their interaction with hazard characteristics is not easily quantified. Similarly to the issues faced for water supplies, a range of hazard and vulnerability characteristics led to the Jenkins et al. (2014) study excluding waste water systems. However, using the DDS and hazard thresholds available (G. Wilson et al. 2014), the Bariloche plant appeared to perform as expected given the tephra fall thickness received (Table 2.9) with temporary disruptions, pump abrasion, and sedimentation in treatment plants the main impacts that occurred (see Table 2.7 for full list of impacts).

Figure 2.11: Bariloche wastewater treatment system A) biological reactor showing some Nocardial foaming; B) and C) sewer lines and junctions inundated with tephra; D) tephra-accelerated pitting and thinning damage to sewage pump impeller.

2.4.2.5 Roading

Route 40 (the main road into Patagonia; sealed, single-laned highway until south of the tephra affected area), Route 231 (between Villa la Angostura and Bariloche; sealed, single-laned highway) and Route 23 (connecting Bariloche and Jacobacci; predominantely unsealed, single-laned, with some one way bridges and sections) all experienced periodic road closures and speed restrictions related to the lack of visibility and issues with vehicular traction on the roads (Table 2.7).

In the temperate zone the major issue facing road users was the volume of tephra on the road. This meant that vehicles were unable to gain traction, and even four-wheel drive vehicles were sometimes unable to use the roads when thicknesses exceeded 100 mm. The volume of tephra and issues with the clogging of air filters also meant that clean up vehicles struggled to gain access to some areas for clean-up. This was overcome by compaction of the deposit and gradual clean-up. The border crossing between Chile and Argentina at the Samore Pass was closed for several weeks as the tephra fall thickness reached over 300mm.

In the Jacobacci and the surrounding steppe region, the lack of visibility meant that no urban clean up of roading started for the first week, slowing the reopening of the town's major roads. Driving conditions in the steppe area remained treacherous for many months after the initial eruption, especially in areas where the tephra fall was thicker than 100 mm (Fig. 2.12 a & b). Due to remobilisation in the area visibility issues persisted in the steppe region and air filters became clogged with tephra and needed cleaning and replacing regularly (Fig. 2.12 c; Table 2.8). Dampening down tephra and restricting vehicle speeds was employed to try and allow traffic to continue using roads (Fig. 2.12 d; Table 2.8). Despite these measures driving remained a challenge on windy days due to the low visibility, even up to 18 months after the eruption.

Figure 2.12: Road conditions in Jacobacci A) poor visibility In Jacobacci (11/7/2011); B) 2WD car outside Jacobacci in ~50mm tephra; C) car air filter clogged with tephra; D) sticker on car window in Jacobacci advising drivers to restrict their speed to 20km/h in order to not "stir up the tephra." (Photo credit: Ailen Rodriguez).

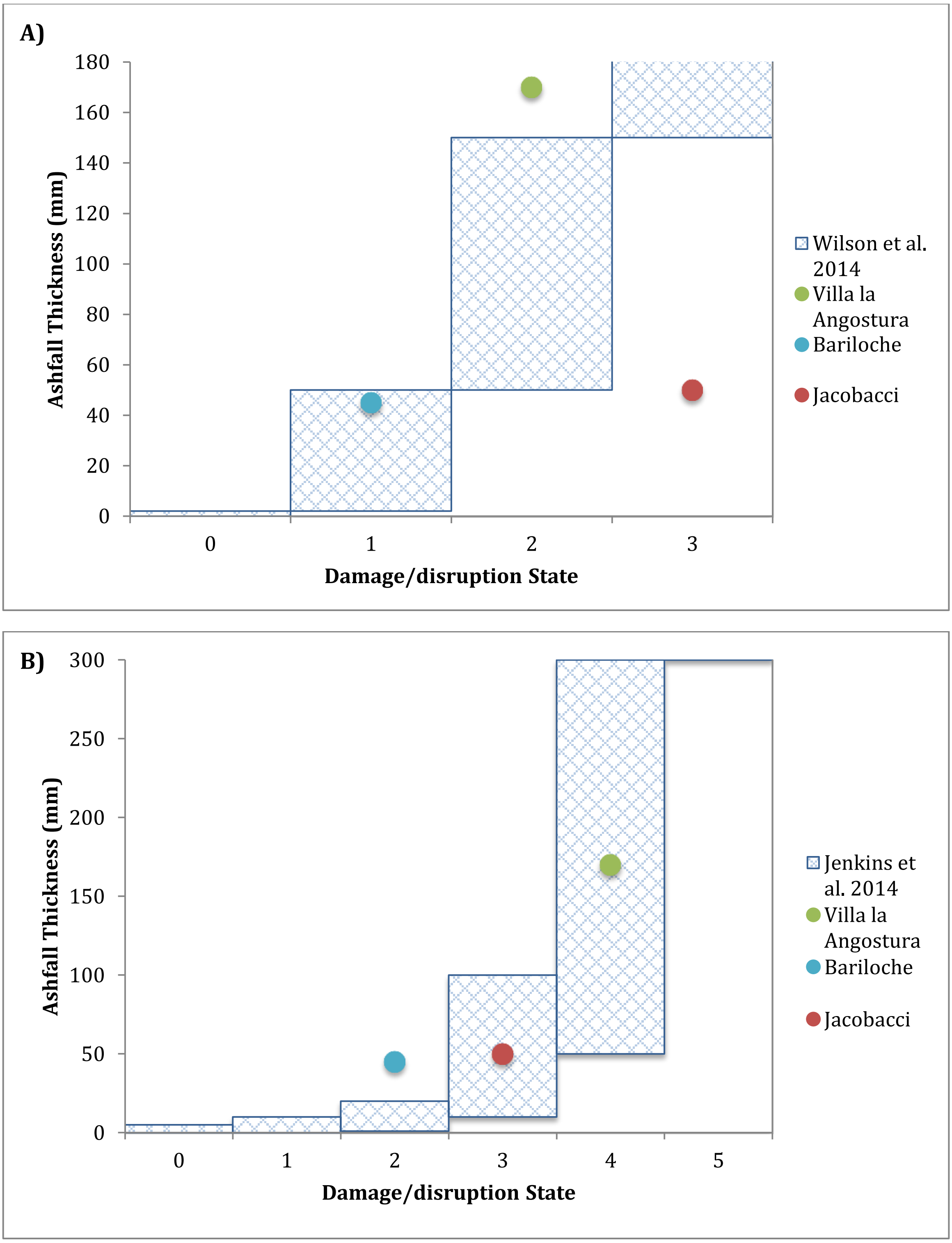


Figure 2.13: Observed damage states for roading across the three main urban centres, compared to hazard intensity ranges given with the A) Jenkins et al. 2014 and B) Wilson et al. 2014 damage state schemes.

Roading networks impacted by the CC-VC tephra fall performed similarly to other eruptions in the region with comparable tephra thicknesses, such as the 1991 Hudson eruption (Wilson et al. 2012c), and the 2008 Chaitén eruption (T.M. Wilson, *unpublished field notes*). Many other eruptions that experienced much lower tephra thicknesses still experienced similar issues with roading networks, demonstrating the low overall resilience of roading to tephra fall (Table 2.6).

Roading in Villa la Angostura (under the G. Wilson et al. 2014 scale) and Bariloche (under the Jenkins et al. 2014 scheme) was able to function better than the thick tephra fall deposits and previous experiences would suggest (Table 2.9; Fig. 2.13). A possible reason for this is that people in the area may have experienced tephra fall before (1961 CC-VC, 1991 Hudson, and 2008 Chaitén eruptions) and therefore have a higher tolerance for the conditions and are more likely to drive. Conversely, DDS predicted lower disruption than what occurred in the Jacobacci steppe region (Table 2.9; Fig. 2.13). This is expected, as the severity and duration of wind remobilisation in the area is much greater than what would be experienced in a temperate region (Wilson et al. 2014; Table 2.8, Fig. 2.12), with wind remobilisation continuing to impact public health and visibility in towns, farming areas and road networks for at least 18 months after the initial tephra fall event. One DDS scale also suggested the possibility of structural damage to some bridge structures due to tephra fall loading, however this was not observed after the CC-VC event even on the Samore Pass, which received tephra fall depths of up to 500 mm, far exceeding the upper limit placed on the highest DDS (>150 mm; G. Wilson et al. 2014).

2.4.2.6 Airport

The closure of Bariloche airport caused major disruption to the tourism industry in the region. The airport closed on the 4 June 2011 and did not reopen for a month, causing economic impacts for a region that relies heavily on both domestic and international tourism (Table 2.7; Fig. 2.14). Airport managers cleaned over 1,000 tonnes of tephra from the runway and surrounding facilities during this time (Table 2.8). Following the clean-up the tephra was deposited in depressions in the surrounding land and revegetated, with the installation of a comprehensive irrigation system accelerating vegetation growth as well as preventing remobilisation and redeposition of the material back onto the runway.

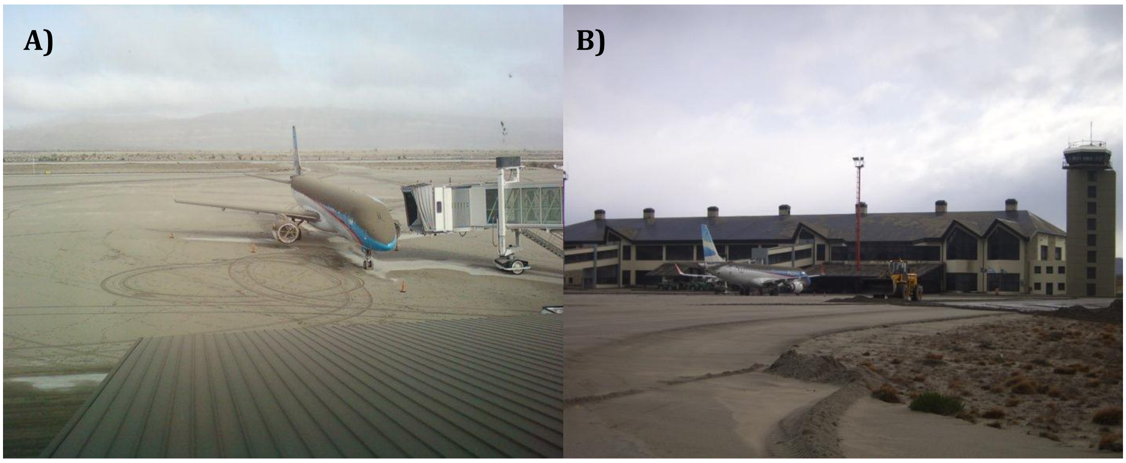


Figure 2.14: Bariloche airport A) tephra covered plane immediately after the initial tephra fall; B) clean up beginning with bulldozers removing tephra from the runway (Photo credit: Bariloche Airport).

Even though the airport re-opened for business on 5 July, it was many more months before the country's two major airlines (LAN Chile and Aerolineas Argentinas) resumed regular services to Bariloche, as eruptive activity continued at Cordón Caulle. The decision to fly rests with individual airlines, with standard procedure to avoid flying through any tephra plume. From the perspective of pilots, the problem was that they did not have a good system for identifying small, diffuse plumes. A further complication was that the tephra forecasting model developed by the National Meteorological Service, and posted on their website for airlines to use, was perceived by airlines as being too 'experimental' according to managers interviewed at Bariloche airport. The acknowledgement of uncertainties associated with the data and modelling deterred airlines from its use. As there were no defined safe parameters for tephra plume density, there was uncertainty about whether insurance companies would continue to provide cover. This meant that the closure at Bariloche airport was longer and therefore more damaging to the local economy (Table 2.8).

Due to the low tolerance of airports to tephra fall (Guffanti et al. 2008), DDS all feature complete closure at low tephra fall thicknesses (≤1 mm). Bariloche airport officials also closed the airport at the first sign of tephra fall, as has occurred after other eruptions in the last 35 years (Table 2.6). DDS both predicted that runway surfaces would suffer some degradation at the thicknesses received in Bariloche, however the extent to which this occurred is unknown as the runway was replaced soon after the eruption. As the runway was scheduled for resurfacing in March 2012, officials chose to bring this forward to October 2011 to take place during the existing disruption due to continued hesitance of airlines to use Bariloche Airport. Due to the majority of airports following standard procedures for total shutdown in tephra fall, the DDS are assessed as accurate predictors of impacts in the CC-VC tephra fall event (Table 2.9).

2.4.2.7 Telecommunications

The most reliable form of communication throughout the emergency was radio (VHF and UHF). In Bariloche, amateur radio operators were instrumental in relaying information. Cellphone networks experienced problems due to overloading of networks. There were anecdotal reports of cell signal attenuation caused by airborne tephra and equipment failure due to deposition of tephra onto ground equipment such as cell phone exchanges, but this was difficult to verify. The 12-hour battery life of antennae came close to being exhausted during the power outages. However, as there was no real damage or widespread disruption to networks due to the tephra fall, available DDS (G. Wilson et al. 2014) were not applied to this sector.

2.5 Urban clean-up

The removal of tephra from streets, public places, business and residential districts was a major focus of the emergency management and recovery effort.

In Villa la Angostura sixteen houses suffered roof collapse, and 40 more were braced to prevent roof collapse. The municipality and wider community undertook a fast and efficient clean-up response. The initial focus was on cleaning the main roads. On the 7 June 2011, 40 km of the main highway (Ruta 231) was closed and cleared with bulldozers then dampened with water tankers (Fig. 2.15 a). Tephra removed by residents with help from volunteer brigades was placed on roadsides then collected by the municipality and taken to provisional tephra dumps, located in each neighbourhood. Material from the dumpsites was then rapidly transferred to an old quarry located in Puerto Manzano (Fig. 2.15 b). At this main dumpsite, compaction and stabilisation of the tephra was undertaken. A further focus of clean-up efforts in Villa la Angostura has been the clearing of natural dams higher up the streams that flow through the town. This was done in an attempt to mitigate the lahar risk as it was thought the dams could cause the build-up of tephra followed by catastrophic failure. Army teams were deployed to cut and clear debris.

Figure 2.15: Photographs showing the Villa la Angostura urban clean-up measures A) Water tanker spraying water along main road to dampen down tephra (March 2012); B) Puerto Manzano quarry tephra dump (March 2012).

Bariloche received up to 45 mm of tephra fall, which equates to approximately 1,500,000 m^3 of material across the urban area. The city did not have sufficient heavy earth-moving machinery for clean-up, and had to hire external machinery and utilise private vehicles. The first area to be cleared was the inner central business district. Clean-up of the city took two months with costs estimated to be some $USD 35 million, not including business disruption losses (estimated by interviewed municipal managers). Residents were encouraged to focus on clearing their own properties and were asked to create just one pile of material per city block to facilitate removal by the municipality. Municipality efforts lasted until December 2011. There were high rates of volunteerism in cleaning the town, particularly in 'high value' areas such as the downtown area important to tourism, and outside schools and hospitals. Most of the collected material (tephra and other urban waste) was disposed of in the old municipal quarry located on the southern fringe of the city. This dump was quickly filled (Fig. 2.16) so new disposal sites were selected. The most important were close to a municipal gas plant where material was accumulated in piles and covered with soil to prevent wind remobilisation; and the municipal dumping site for waste from forestry activities. During the first two days of tephra fall some tephra was also dumped in the lake both in Villa La Angostura and Bariloche.

Figure 2.16: Compacted tephra dumpsite on outskirts of Bariloche. Previously there was a small depression that was filled by the dumpsite.

In Jacobacci, clean-up operations were delayed for a week because of extremely poor visibility. The main streets were cleared first, using all available trucks, diggers and bulldozers in the town (Fig. 2.17 a). Following this, residents were provided with large sacks to fill with tephra cleared from their own properties (Fig. 2.17 b,c, & d). Collected tephra was dumped in natural depressions to the east (downwind) of the town, and weighed down with waste building materials in a short-term attempt at stabilisation. In the longer term, there were plans to vegetate the deposits. Clean-up operations in Jacobacci were made significantly more difficult because of constant problems with wind remobilisation of unconsolidated tephra deposits, not only within the urban area but also from upwind sources. This meant that clean-up operations had to be coordinated and carried out numerous times following every major wind storm tephra remobilisation event.

Clean-up of the tephra fall had an immediate effect on the impacts to critical infrastructure that the urban centres were undergoing as a result of the tephra fall. Organised and proactive cleaning of power lines and insulators in Villa la Angostura meant that while many flashover events occurred the network still remained functional after a few days of tephra fall. Similarly, at the water treatment plant in Bariloche, rotational cleaning of sand filters (one sand bed taken out of use for thorough cleaning every ten days) was effective, and despite supplies being stretched the system mostly coped. Urban clean-up is the most effective mitigation tool available to emergency managers and allows for rapid restoration of critical infrastructure services (Hayes et al. 2015).

Figure 2.17: Tephra removal from main street of Jacobacci (9/6/2011); A) Bulldozer removing tephra from the main street; B) Residents sweeping dry tephra off roofs with brooms; C) Piling tephra into collection piles on the road for municipal collection; D) People cleaning tephra fall from a community playground. Photo credits: Ailén Rodriguez (A) and Jose Mellado (B, C, D).

Previous assessments of urban tephra fall clean-up have shown that urban areas with large tephra fall accumulation will remove the majority of the tephra material, whereas areas with lower accumulation will remove a smaller proportion of this (Hayes et al. 2015). This trend was not shown after the CC-VC event, where clean-up in Villa la Angostura removed approximately 20,000 $m^3$of tephra per km^2 (although tephra fall accumulation was ~300,000 m^3/km^2), compared to Bariloche where a similar amount of material was removed (~15,000 m^3 of tephra per km^3) despite experiencing much lower tephra accumulation (~35,000 m^3/km^2) (Hayes et al. 2015). Although amounts of tephra fall material collected and dumped in Jacobacci are not known, it is likely that this would have been low regardless of tephra fall accumulation amounts, as continued wind remobilisation meant clean-up operations were needed repeatedly and focussed mainly on essential areas such as main roads and schools. Tephra fall accumulation thresholds for clean-up actions are proposed by Hayes et al. (2015), the accumulation for Bariloche and Jacobacci compares relatively well with the predicted and actual clean-up actions (Fig. 2.18). Whilst this is a relatively generalised scale it still provides some indication as to the different actions taken. This shows that although the actions taken correlate well with the categories suggested by Hayes et al. (2015), the amount of tephra actually removed and dumped comprises a smaller percentage of the total tephra accumulation than expected based on previous events. There are a number of possible explanations for this, including that tephra dumping was not always undertaken using official guidelines or well recorded or that residents in the area were relatively tolerant to tephra on private properties.

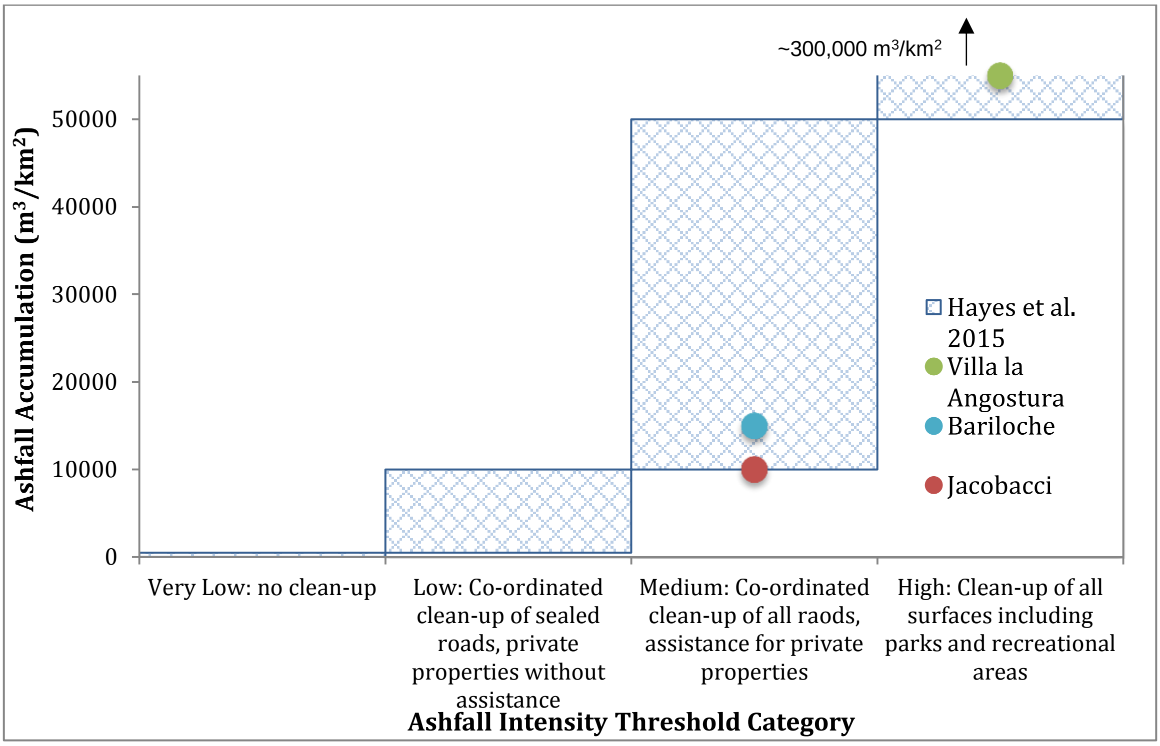


Figure 2.18: Clean-up thresholds with damage thicknesses from Hayes et al. 2015, compared to actual clean-up actions and tephra accumulation in the three main centres affected by the 2011 CC-VC tephra fall.

2.6 Discussion

The most notable aspect of the tephra fall impacts from the 2011 CC-VC eruption was the divide between the temperate region (including Villa la Angostura and Bariloche) and the semi-arid steppe (including Jacobacci). Despite receiving smaller tephra fall thicknesses, the impacts in the steppe region were more severe than the temperate zone. This is due to the unique environmental conditions that caused extreme, prolonged wind remobilisation of the tephra fall deposit. This caused conditions similar to those at the time of deposition over the period of many months leading to prolonged disruption to infrastructure and primary industry. This was similar to the more severe impacts in the steppe area after the 1991 Hudson eruption, where wind remobilisation and 'tephra storms' slowed recovery over many years (Wilson et al. 2011b). In contrast, the thicker, coarser deposits in the temperate zone stabilised relatively rapidly, meaning that recovery could begin within weeks of the tephra fall events. This created two distinct areas of impacts and recovery times, which required different management and mitigation strategies.

Overall, the majority of the CC-VC impacts were similar to those experienced after previous tephra fall events, especially compared to the 1991 Hudson and 2008 Chaitén eruptions that also took place within the Patagonian region (Table 2.6). However, when comparing impacts to agriculture and infrastructure to thickness thresholds placed on DDS scales, the temperate region of Nahuel Huapi National Park, and Villa la Angostura and Bariloche townships consistently had fewer severe impacts than expected under high thicknesses of tephra fall (>150 mm in Villa la Angostura and >30 mm in Bariloche) (Tables 2.5, 2.9 & 2.10). Impacts mainly resulted in infrastructure disruption rather than long-term damage, and most sectors recovered with the removal of tephra and minimal intervention and repairs. If the damage predicted by tephra fall thicknesses had occurred recovery would have taken months to years, and financial losses to the region would have been more severe. This is likely due to the damage state thresholds not accounting for mitigating factors (such as the high rainfall levels hastening the incorporation of tephra into the soil, preventing remobilisation, and rinsing infrastructure such as electrical systems and roading), which resulted in the higher resilience to tephra fall in Villa la Angostura and Bariloche. An unexpected outcome was the matching of observed impacts in the Jacobacci and steppe region, with those predicted by the tephra fall thickness thresholds associated with the DDS (Tables 2.5, 2.9 & 2.10). As the extreme climate (very low precipitation, <150 mm/year) resulted in the nature of the impacts being largely determined by the severe wind remobilisation, it is unlikely that temperate areas would have the same impacts at similar tephra fall thicknesses. This could restrict the application of the hazard thresholds to future events that do not undergo substantial wind remobilisation.

Table 2.10: Summary of how key infrastructure and agricultural systems performed compared to damage states assigned based on tephra thickness thresholds.

		Villa la Angostura	Bariloche	Jacobacci
Electricity	G. Wilson et al. 2014	Better	Better	Same
	Jenkins et al. 2014	Better	Same	Same
Water	G. Wilson et al. 2014	Better	Same	Better
	Jenkins et al. 2014	NS	NS	NS
Waste water	G. Wilson et al. 2014	NI	NI	NI
	Jenkins et al. 2014	NS	NS	NS
Roading	G. Wilson et al. 2014	Better	Same	Same
	Jenkins et al. 2014	Same	Better	Same
Airports	G. Wilson et al. 2014	NI	Same	NI
	Jenkins et al. 2014	NI	Same	NI
		Nahuel Huapi National Park	**Steppe region**	
Agriculture	Wilson et al. 2009	Better	Better	
	Jenkins et al. 2014	Same	Same	

NS: Denotes where no damage state scheme was developed.

NI: Denotes where sites were not investigated during this study.

A limitation of this study is the relatively small number of interviews undertaken and the assumption that the information collected during the post-EIA is representative. This was accounted for by including interviews with municipal level staff, which gave insight into broad municipal and regional level trends. Interviews with individual farmers and stakeholders correlated well with these regional scale interviewee perspectives.

Another factor that determines the DDS of a sector are the emergency response actions taken by managers or stakeholders after the event. The schemes integrate management decisions into the impact descriptors, meaning that decision-makers can influence the DDS, independent of the actual thicknesses received. This is particularly evident when considering roading impacts, where road closures and types of cars on the road are considered. In areas where tephra fall has occurred before or the event is prolonged over many months, such as in the steppe region of this case study, emergency managers may be less likely to close roads and drivers more confident of their ability to drive on them compared to a region that had not experienced significant tephra fall before. For example after the 2012 Tongariro eruption in New Zealand, the main state highway in the area was closed following <3 mm of tephra fall (Jolly et al. 2014; Leonard et al. 2014). In contrast, roads remained open in the Bariloche and Jacobacci regions, despite receiving up to 50 mm of tephra fall. This different risk tolerance can impact which DDS a sector falls under, independent of the hazard intensities that occurred. The risk tolerance of individuals could potentially have a significant effect on the perceived hazard and its impacts (Paton et al. 2008; Johnston et al. 1999). This is important to consider when relying on data gathered during interviews. Previous events have demonstrated that peoples perception of impacts due to volcanic hazards change based on their previous experiences (Sword-Daniels et al. 2014). In the CC-VC context this could mean that participants that also experienced previous tephra fall events, such as the 1960 CC-VC eruption that affected parts of the Nahuel Huapi National Park (Chapron et al. 2006) or the 2008 Chaitén eruption that deposited up to 2 mm of tephra in the Pilcaniyeu area (Watt et al. 2009), may be perceive the impacts (and therefore the resulting DPS) to be greater or lesser dependent on whether the impacts were more or less severe than those that occurred previously (Weinstein 1989).

The utility of DDS and their associated hazard intensities as a pre-event predictive tool is limited by a number of factors. Pre-EIA aims to forecast the effect that a hazardous event will have on an exposed system usually through a qualitative assessment, unlike risk assessments that have numerical probabilities attached to them. As impact is defined as a function of the hazard, and the exposed assets and their vulnerabilities (ISDR 2009), pre-EIA need to incorporate information on all these elements. Therefore, applying the DDS on hazard maps or models can be challenging, as they only take into account one hazard intensity measure (thickness) and do not consider the design or vulnerability of the exposed assets, or whether mitigation measures to minimise losses are in place. Another possible limitation of using the states as a forecasting method is that they are based on information that has been collected from various events during the limited number of available post-EIA. This means that they are likely to have been taken from information that will be biased towards the more extreme impacts, as assessment teams often look to assess impacts and damage rather than resilience. This could be a possible explanation for why the temperate region (Villa la Angostura and

Bariloche) was not affected by the high severity impacts predicted, whereas the semi-arid region (Jacobacci) which was much more vulnerable than many other areas worldwide, received the impacts forecasted by the states. Current post-EIA research is moving towards eliminating this bias by adopting guidelines used after other hazards that recommend statistically robust assessment methods, such in as tsunami research (Chagué-Goff et al. 2012; Szczucinski et al. 2006; Wilson et al. 2014). However, despite these limitations, in the absence of further information the thresholds have shown, using the CC-VC case study and others, that they provide some indication of potential impacts.

One of the most useful applications of the DDS scales is to quantify observations taken during post-EIA. This allows qualitative statements to be placed into a framework suitable for comparisons, and trends across different affected areas to be assessed. This application is similar to how the Modified Mercalli (MM) scale (Wood & Neumann 1931) and the more recent European Macroseismic Scale (EMS) (Musson et al. 2009) are used to describe damage and human experience during an earthquake. As with tephra DDS, there have been a series of attempts to accurately assign hazard intensities to each scale. For these scales research has focussed on matching the scales with ground acceleration, velocity and displacements (Lliboutry 1999; Wald et al. 1999). The assumptions necessary to calculate the corresponding hazard intensities mean that other risk assessment methods, such as numerical modelling of specific repair costs with hazard intensities, are still preferable forecasting tools (Rossetto et al. 2014). Volcanic risk assessments lack the strong empirical dataset that earthquake research possesses (Wilson et al. 2014), therefore hazard thresholds and damage descriptors based on 'expert judgement' are often the only available predictive tool. This means that continued refinement of hazard thresholds and the incorporation of vulnerability information and other factors external to the tephra fall into schemes is necessary to increase predictive capacity (Fig. 2.19). As a consequence a different set of thresholds will need to be identified for different climatic regions, system types and design, and possibly other vulnerability characteristics in order to refine pre-event impact assessments.

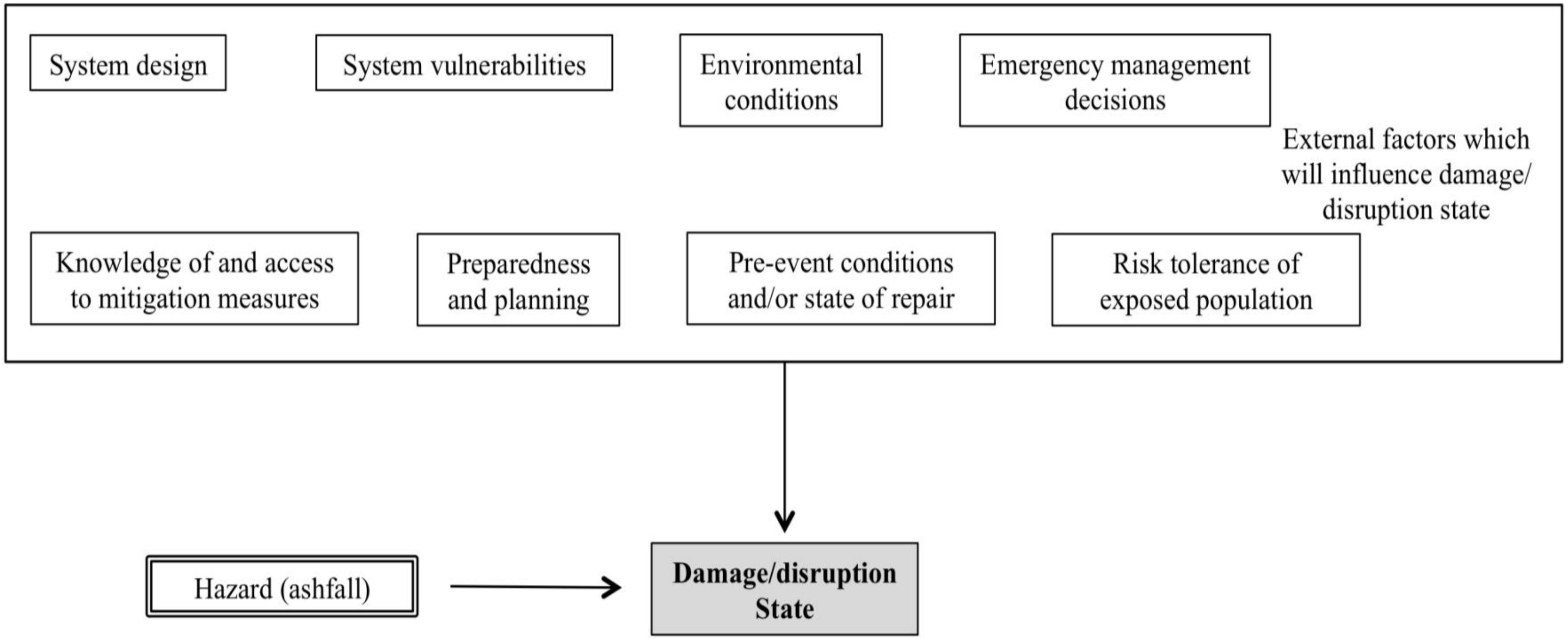


Figure 2.19: Diagram of factors that can contribute to the observed damage/disruption state, external to the tephra fall deposit characteristics.

2.6.1 Towards universal damage/disruption state schemes

In order to predict the impacts (or DDS) to a system, understanding the hazard and its intensity (e.g., tephra fall thickness) is vital. However, an understanding of the vulnerability of the affected system is also needed (Alexander 2002). This includes contextual information such as systems design, the pre-existing condition and maintenance, and the season and climatic zone the tephra fall was deposited in. This means that any hazard intensity thresholds placed on DDS or impact classification schemes need to be tailored for specific regions and infrastructure and primary industry types.

Despite the challenges of incorporating systems with different vulnerabilities, the pursuit of a set of DDS that can be universally applied after tephra fall, both as a forecasting tool and a means of categorising damage during post-EIA, has continued for many years (Blong 2003a & b). The infrequent nature of large volcanic eruptions and variations in eruption types, characteristics and spatial impact means there will always be challenges in creating a universal system based on data aggregated from across different events. Therefore, whilst there are many challenges in developing a universally applicable DDS, future refinement and development of continuing attempts should include:

- The creation of different DDS schemes for different infrastructure designs and agricultural types. The specific properties that DDS schemes were designed for should be outlined in accompanying material so that they can be used with caution for different systems. This is especially pertinent when considering water and wastewater systems that have high, and location-dependent, variability in their design.
- Numerous factors external to the tephra fall deposit characteristics that influence the impacts to critical infrastructure and agricultural systems (Fig. 2.19). These factors need to be considered when creating and refining DDS. It is likely that different hazard intensity thresholds (in this case tephra fall thicknesses) for each

DDS will need to be identified for different system designs and environmental conditions.

- On-going refinement and standardisation of existing schemes, rather than the creation of new ones. Both the Jenkins et al. 2014 and the G. Wilson et al. 2014 schemes provide a sufficient framework for continued refinement of thresholds and descriptors as more empirical and analytical data becomes available. This allows for more accurate thresholds to be assigned and is more beneficial to the field than the continued development of new schemes.
- DDS developers need to acknowledge two main uses for the schemes (forecasting tools during pre-EIA and as a method of categorising impact information during post-EIA) and incorporate instructions on how best to apply the states in each scenario.
- A clearly outlined and defined distinction between damage and disruption (or functionality).
- Tephra fall thicknesses associated with each state should be given as a range that overlaps with the thicknesses given for the previous state, which is a strength of the Jenkins et al. 2014 scheme. This is likely to be more accurate when applied to case studies, as it is unlikely that there would be a vast jump in damage and/or disruption due to an extra millimetre of tephra being deposited on an area, rather there would be a gradual increase in damage with increasing tephra fall thickness. This approach also better accounts for the variation in impacts across areas, even when similar tephra fall thicknesses are measured.
- Continued application and validation of DDS schemes to case studies is necessary to improve accuracy of hazard thresholds and associated descriptors. This needs to be undertaken in a variety of settings for all infrastructure and agricultural sectors. Additionally, assessment by researchers not involved in the development of the DDS is advantageous to proving repeatability and usability.

2.7 Conclusions

Overall, tephra fall impacts to infrastructure and agriculture after the 2011 CC-VC eruption were broadly similar to impacts observed elsewhere after comparable tephra fall events. This event was notable, however, due to the contrasting impacts, management, and recovery between the two climatic regions. Severe wind remobilisation in the semi-arid steppe region (including the town of Jacobacci) meant although tephra fall thicknesses were much lower, the DDS observed were often the same as those experienced in areas more proximal to the volcano that received much greater tephra fall thicknesses. Conversely, impacts were minimised and recovery aided by the temperate environment and management response in Villa la Angostura and Bariloche. This climatic division of impacts has been recorded elsewhere, notably after the 1991 Hudson eruption (Wilson et al. 2011a).

Application of DDS by their associated hazard intensity thresholds (tephra fall thickness) showed a relatively good correlation of impacts with thicknesses for the Jacobacci and semi-arid steppe region (except for water systems which performed better than predicted by the DDS) (Table 2.10). This was unexpected due to the unique conditions and extreme wind remobilisation. The temperate region (including Villa la Angostura and Bariloche) experienced less severe impacts than tephra fall thicknesses indicated, with critical infrastructure networks mostly returning to full functionality within weeks of the initial event. This indicates the limitations of using DDS as the sole predictor of impacts and suggests refinement of hazard thresholds and increased consideration of system types and design, and environmental and vulnerability characteristics is required.

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2.9 References

Aguirre, A. (2012). Estudio del impacto de las cenizas volcánicas en el proceso de esquila. Bariloche.

Alexander, D. (2002). Principles of emergency planning and management. New York: Oxford University Press.

Blong, R. (2003a). A new damage index. Nat. Hazards, 30, 1–23.

Blong, R. (2003b). A Review of Damage Intensity Scales. Nat. Hazards, 29, 57–76.

Buteler, M., Stadler, T., López, G. P., Lassa, M. S., Liaudat, D. T., & Fernandez-arhex, D. A. V. (2011). Propiedades insecticidas de la ceniza del complejo volcánico Puyehue-Cordón Caulle y su posible impacto ambiental, 70, 149–156.

Chagué-Goff, C., Niedzielski, P., Wong, H. K. Y., Szczuciński, W., Sugawara, D., & Goff, J. (2012). Environmental impact assessment of the 2011 Tohoku-oki tsunami on the Sendai Plain. Sediment Geol, 282, 175–187.

Chapron, E., Ariztegui, D., Mulsow, S., Villarosa, G., Pino, M., Outes, V., … Crivelli, E. (2006). Impact of the 1960 major subduction earthquake in Northern Patagonia (Chile, Argentina). Quaternary International, 158(1), 58–71. http://doi.org/10.1016/j.quaint.2006.05.017

Departamento Provincial de Aguas. (2011). Análisis de Registros Pluviométrico – Estación Jacobacci.

Dingwell, D. B., Lavallée, Y., & Kueppers, U. (2011). Volcanic ash: A primary agent in the Earth system. J. Phys. Chem. Earth, Pts A/B/C, 2010–2012.

Easdale, M. H., Sacchero, D., Vigna, M., & Willems, P. (2014). Assessing the magnitude of impact of volcanic ash deposits on Merino wool production and fibre traits in the context of a drought in North-west Patagonia, Argentina. The Rangeland Journal, 36(2), 143–149.

Flueck, W. (2013). Effects of fluoride intoxication on teeth of livestock due to recent volcanic eruption in Patagonia, Argentina. OJVR, 14(4), 167–176.

Flueck, W. T. (2014). Continuing impacts on red deer from a volcanic eruption in 2011. Eur. J. Wildl. Res.

Flueck, W. T., & Smith-Flueck, J. A. M. (2013). Severe dental fluorosis in juvenile deer linked to a recent volcanic eruption in Patagonia. J. Wildl. Dis, 49(2), 355–66.

Guffanti, M., Mayberry, G. C., Casadevall, T. J., & Wunderman, R. (2008). Volcanic hazards to airports. Nat. Hazards, 51(2), 287–302.

Hayes, J. L., Wilson, T. M., & Magill, C. (2015). Tephra fall clean-up in urban environments. Journal of Volcanology and Geothermal Research, 204(October), 359-377.

ISDR. (2009). 2009 UNISDR Terminology on Disaster Risk Reduction. Geneva, Switzerland.

Jenkins, S. F., Wilson, T. M., Magill, C. R., Miller, V., & Stewart, C. (2014). Volcanic ash fall hazard and risk: Technical background paper for the UN-ISDR Global Assessment Report on Disaster Risk Reduction 2015. Mln (Vol. 120). Retrieved from http://muse.jhu.edu/content/crossref/journals/mln/v120/120.3contributors.html

Johnston, D. M. (1997). Physical, and social impacts of past and future volcanic eruptions in New Zealand. PhD thesis, Massey University.

Johnston, D. M., Bebbington, M. S., Lai, C. D., Houghton, B. F., & Paton, D. (1999). Volcanic hazard perceptions: comparative shifts in knowledge and risk. Disaster Prevention and Management, 8(2), 118–126.

Jolly, G. E., Keys, H. J. R., Procter, J. N., & Deligne, N. I. (2014). Overview of the co-ordinated risk-based approach to science and management response and recovery for the 2012 eruptions of Tongariro volcano, New Zealand. J. Volcanol. Geotherm. Res., 286, 184–207.

Leonard, G. S., Stewart, C., Wilson, T. M., Procter, J. N., Scott, B. J., Keys, H. J., … McBride, S. K. (2014). Integrating multidisciplinary science, modelling and impact data into evolving, syn-event volcanic hazard mapping and communication: A case study from the 2012 Tongariro eruption crisis, New Zealand. J. Volcanol. Geotherm. Res., 286(2014), 208–232.

Lliboutry, L. (1999). Quantitative geophysics and geology. Paris: Masson.

Musson, R. M. W., Grünthal, G., & Stucchi, M. (2009). The comparison of macroseismic intensity scales. J. Seismol., 14(2), 413–428.

Neild, J., Flaherty, P. O., Hedley, P., Underwood, R., Johnston, D., Christenson, B., & Brown, P. (1998). Impact of a volcanic eruption on agriculture and forestry in New Zealand. MAF policy technical paper 99/2, 92p.

OVDAS-SERNAGEOMIN. (2011). Volcanic Activity 2010/2011. Retrieved January 12, 2012, from http://www2.sernageomin.cl/ovdas/ovdas7/informativos2/Informes/Reportes/RegionXIV/RAV_N254_Los-Rios_03012012.pdf

Paton, D., Smith, L., Daly, M., & Johnston, D. (2008). Risk perception and volcanic hazard mitigation: Individual and social perspectives. Journal of Volcanology and Geothermal Research, 172(3-4), 179–188. http://doi.org/10.1016/j.jvolgeores.2007.12.026

Peel, M. C., Finlayson, B. L., & Mcmahon, T. A. (2007). Updated world map of the Koppen-Geiger climate classification. Hydrol. Earth Syst. Sci., 11, 1633–1644.

Robles, C. A. (2012). Consecuencias de la erupcion volcanica sobre la salud del ganado en la region Patagonia. Bariloche.

Rossetto, T., Ioannou, I., Grant, D. N., & Maqsood, T. (2014). Guidelines for Empirical Vulnerability Assessment Report produced in the context of the Vulnerability Global Component project. Pavia.

Salazar, J., Godagnone, R., & Marcolin, A. (1982). Relevamiento integrado de recursos naturales de Rio Negro. S. C. de Bariloche.

Schipper, C. I., Tuffen, H., & Castro, J. M. (2012). Shallow vent architecture of Puyehue Cordón-Caulle , as revealed by direct observation of explosive activity. Geophysical Research Abstracts, 14(1).

Servicio Meteorologico Nacional. (2012). Climatologia.

Shoji, S., Nanzyo, M., & Dahlgren, R. A. (1993). Volcanic Ash Soil. Amsterdam: Elsevier Science.

Smithsonian. (2014). Puyehue-Cordon Caulle Weekly Reports. Retrieved January 5, 2014, from http://www.volcano.si.edu/world/volcano.cfm?vnum=1507-15=

Sword-Daniels, V., Wilson, T. M., Sargeant, S., Rossetto, T., Twigg, J., Johnston, D. M., Loughlin, S. C., & Cole, P. D. (2014). Chapter 26 Consequences of long-term volcanic activity for essential services in Montserrat: challenges, adaptations and resilience. Geological Society, London, Memoirs, 39(1), 471–488. http://doi.org/10.1144/M39.26

Szczucinski, W., Chaimanee, N., Niedzielski, P., Rachlewicz, G., Saisuttichai, D., Tepsuwan, T., Lorenc, S., & Siepak, J. (2006). Environmental and geological impacts of the 26 December 2004 tsunami in coastal zone of Thailand-overview of short and long-term effects. Polish J. of Environ. Stud., 15(5), 793–810.

Wald, D. J., Quitoriano, V., Heaton, T. H., & Kanamori, H. (1999). Relationships between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California. Earthquake Spectra, 15(3), 557–564.

Wardman, J. B., Wilson, T. M., Bodger, P. S., Cole, J. W., & Stewart, C. (2012). Potential impacts from tephra fall to electric power systems: a review and mitigation strategies. Bull. Volcanol., 74(10), 2221 - 2241.

Watt, S. F. L., Pyle, D. M., Mather, T. A., Martin, R. S., & Matthews, N. E. (2009). Fallout and distribution of volcanic ash over Argentina following the May 2008 explosive eruption of Chaitén, Chile. Journal of Geophysical Research, 114(B4), 1–11. http://doi.org/10.1029/2008JB006219

Weinstein, N. D. (1989). Effects of personal experience on self-protective behavior. Psychological Bulletin, 105(1), 31–50. http://doi.org/10.1037/0033-2909.105.1.31

Wilson, G., Wilson, T. M., Deligne, N. I., & Cole, J. W. (2014). Volcanic hazard impacts to critical infrastructure: A review. J. Volcanol. Geotherm. Res., 286, 148–182.

Wilson, R., Wood, N., Kong, L., Shulters, M., Richards, K., Dunbar, P., … Young, E. (2014). A protocol for coordinating post-tsunami field reconnaissance efforts in the USA. Nat. Hazards, 75(3), 2153–2165.

Wilson, T., Cole, J., Cronin, S., Stewart, C., & Johnston, D. (2011a). Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: lessons for recovery. Nat. Hazards, 57(2), 185–212.

Wilson, T., Cole, J., Johnston, D., Cronin, S., Stewart, C., & Dantas, A. (2012). Short- and long-term evacuation of people and livestock during a volcanic crisis: lessons from the 1991 eruption of Volcan Hudson, Chile. J. Applied Volcan., 1(1), 2.

Wilson, T., Cronin, S., Cole, J., & Johnston, D. (2009). Impacts and rehabilitation of pasture following volcanic ashfall. In Vulnerability of pastoral farming systems to volcanic ashfall hazards (pp. 71–126). Dissertation, University of Canterbury.

Wilson, T. M., Cole, J. W., Stewart, C., Cronin, S. J., & Johnston, D. M. (2011b). Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. Bull. Volcanol., 73, 223–239.

Wilson, T. M., Stewart, C., Sword-Daniels, V., Leonard, G. S., Johnston, D. M., Cole, J. W., Wardman, J, Wilson, G. & Barnard, S. T. (2012a). Volcanic ash impacts on critical infrastructure. Phys. Chem. Earth, Parts A/B/C, 45-46, 5–23.

Wilson, T., Stewart, C., Bickerton, H., Baxter, P., Outes, V., Villarosa, G., & Rovere, E. (2012b). The health and environmental impacts of the June 2011 Puyehue-Cordón Caulle volcanic complex eruption: a report on the findings of a multidisciplinary team. GNS Science Report 2012/20.

Wilson, T., Stewart, C., & Wardman, J. (2014). Volcanic ashfall preparedness poster series: a collaborative process for reducing the vulnerability of critical infrastructure. J. Applied Volcanol., (2), 1–25.

Wood, H., & Neumann, F. (1931). Modified Mercalli intensity scale of 1931. Bulletin of the Seismological Society of America, 21(4), 277–283.

Chapter Three
Availability of ash leachates from the 2011 Cordón Caulle – Volcanic Complex eruption: implications for agricultural systems

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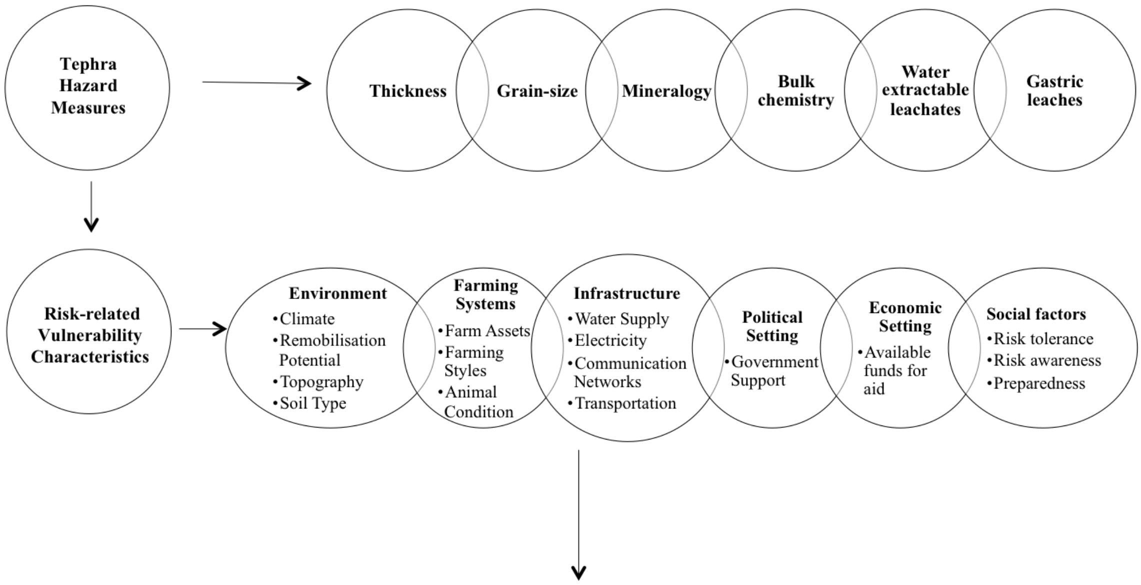
3.1 Abstract

The June 2011 Cordón Caulle Volcanic Complex (CC-VC) eruption sequence (Northern Patagonia, Chile) dispersed volcanic ash over a wide area (>75,000 km^2), covering a large amount of productive agricultural land in two distinct environmental settings (temperate Andean and the semi-arid Argentine steppe). Freshly-deposited ash was sampled between 4 and 26 June 2011 at distances of 45 to 235 km from the volcano, and again between 4 and 13 March 2012 at comparable distances. Total and water-extractable element concentrations were determined in these samples to assess the agricultural hazards associated with readily available elements and evaluate any change in the leachable properties of the ashfall over nine months. Testing was undertaken according to a recent leachate analysis protocol endorsed by the International Volcanic Health Hazards Network with the aim of contributing further towards the refinement of loss thresholds for agriculture. Evaluation of the hazards from potentially toxic elements (e.g., Fluoride) showed that the widespread losses observed were most likely due to

physical impacts (such as smothering of feed, tooth abrasion and rumen blockages) rather than toxicity. Within the semi-arid zone, extensive wind-remobilisation of ash deposits occurred, but no difference was found between water-extractable element concentrations in epiclastic and *in situ* deposits collected in 2012. Water-extractable element concentrations in freshly collected (2011) ash showed no systematic trends with distance from the volcano. However, in the samples collected in 2012, concentrations of water-extractable elements were generally lower than in 2011, but increased with increasing distance from the volcano. This difference is readily explained in terms of climatic differences across the sampling transect, with water-extractable elements apparently conserved in the semi-arid conditions of the steppe. Undertaking a full assessment of environmentally available elements from the ashfall deposit is an essential input into holistic hazard assessments. A full understanding of the environmentally-available element composition of the ash is necessary for identifying potential toxicity issues, which may prompt specific mitigation measures. However, urgent work is needed to better define toxicity thresholds for pasture and livestock related to ash ingestion, to inform future hazard and risk assessments.

3.2 Introduction

Volcanic ashfall has the potential to cause widespread agricultural and economic losses. Productive, fertile soils are often formed from long-term weathering products of volcanic deposits (Shoji et al. 1993), therefore, agricultural areas are frequently concentrated in volcanically active regions leaving them vulnerable to widespread ashfall and other volcanic hazards. Agricultural losses can occur by both physical and chemical mechanisms (Ayris & Delmelle 2012). Crop losses have most commonly been due to physical overloading and burial or breakage of plants, and livestock deaths due to starvation, dehydration and gastrointestinal blockages (Wilson et al. 2011a; Cook et al. 1981; Cronin et al. 1998; Rubin et al. 1994). See Appendix A.1 for a review of previous events and associated impacts. Whilst there have been cases of animal poisoning due to ash toxicity, especially associated with fluoride and in some cases sulphur, these are relatively rare but high consequence events (Cronin et al. 2003; Thorarinsson & Sigvaldason 1971). The possible severe productivity losses and negative animal health consequences means that despite its rarity, it is very common for farmers and agricultural managers to be concerned about F toxicity hazards following an ashfall (Cook et al. 1981; Cronin et al. 2003; Wilson et al. 2011a). Therefore, it is vital that water and total leachable F concentrations are assessed to accurately quantify potential toxicity and disseminate risk information to farmers.



	Soil	Vegetation	Animal Health
Physical	Ash permeability Cementation of ash Lowering of soil temperature Positive mulching effect	Burial Overloading Photosynthesis prevented	Rumen blockages Feed and water sources unpalatable Starvation Tooth abrasion
Chemical	Soil acidity Low Cation Exchange Capacity Beneficial amounts of elements (i.e., S) Addition of toxic elements	Chemical burns Uptake of elements Root apex damage	Fluorosis

Figure 3.1: Outline of hazard and risk assessment factors needed to be considered in order to forecast and understand ashfall impacts to agricultural systems.

Risk assessments seek to predict the likelihood and consequences of a hazard by evaluating the pre-existing conditions in an area, as well as taking into account the hazardous nature of deposited ash (UN-ISDR 2009). To minimise agricultural losses after an explosive eruption a timely hazard and risk assessment of the fall deposit is needed to inform emergency response decision-making and recovery planning (Fig. 3.1). Such hazard assessments seek to quantify the properties of the ashfall deposit that are likely to cause impacts to the affected area. Understanding ashfall hazards allows for an assessment of risk and, if required, the initiation of risk management strategies. In the case of volcanic ashfall on agricultural systems, a risk model needs to take into account the deposit properties (such as grain size, leachable elements, bulk composition, thickness, loading, etc.), and vulnerability characteristics such as the environmental, agricultural, political, social and economic characteristics of the affected region (Fig. 3.1). Traditionally, there has been a focus on correlating impacts with the thickness or loading of the deposit (Jenkins et al. 2014; Wilson et al. 2014). However, there is an increasing focus on incorporating other factors (such as the leachable element concentration) into risk models. Agricultural losses do not always occur immediately after the ashfall but can manifest over the following weeks, months and even years (Cook et al. 1981; Cronin et al. 2003; Wilson et al. 2011b). Understanding the hazard and risk to farming gives an opportunity to minimise medium to long-term impacts (Wilson et al. 2009). The development of a risk model and the identification of any risk factors ensures that management strategies can be targeted to specific problems in order to minimise losses (Alexander 2002).

Characterisation of the physical and chemical properties of the ash deposit is an important component of a risk assessment for agricultural systems affected by ashfall (Fig. 3.1). Whilst the collection of physical hazard data (such as mapping the extent, thickness, and grain size of the deposit) is undertaken using well-constrained methods, analysis of environmentally-available elements from the ash deposits has previously been done using a range of non-standardised methods. This lack of standardisation limits the usefulness of results and does not allow for comparison or knowledge transfer between events. These issues have led to the development of a standardised protocol for characterising leachable element properties of ashfall (Stewart et al., 2013).

This study presents data on leachable elements in both fresh and weathered (after approximately nine months) ash deposits, an evaluation of gastrically available F from fresh ash deposits, and surface water composition in the depositional zone of the ashfall. The impact of the ashfall on soil fertility has also been assessed, nine months after the eruption. This study applies the methods for assessing the hazard of leachable elements (developed by the International Volcanic Health Hazards Network and available at www.ivhhn.org; Stewart et al. 2013), after a large-scale, silicic eruption to an agricultural context. The Cordón Caulle – Volcanic Complex (CC-VC) ashfall also provided an opportunity to assess the fate of tephra introduced elements from the same deposit over two contrasting environmental zones, as the fallout area extended from the temperate Andean zone to the semi-arid Argentine steppe.

3.3 2011 Cordón Caulle eruption

The Cordón Caulle Volcanic Complex (CC-VC) is located in the Southern Andes of Chile (40.5°S) (Francis 1976) (Fig. 3.2). It is comprised of a Pleistocene caldera at the north-western end (Cordillera Nevada), a Holocene stratovolcano (Puyehue), and the Cordón Caulle fissure complex that lies between these edifices. The 2,236 m high Puyehue stratovolcano formed on top of an older 5 km-wide caldera, is flat-topped and has a 2.4 km wide summit caldera. It lies to the south of the older, less-active Mencheca stratocone. The most recently active section of the complex is the Cordón Caulle fissure zone, although historic eruptions have often been incorrectly attributed to Puyehue (Singer et al. 2008; Smithsonian 2011).

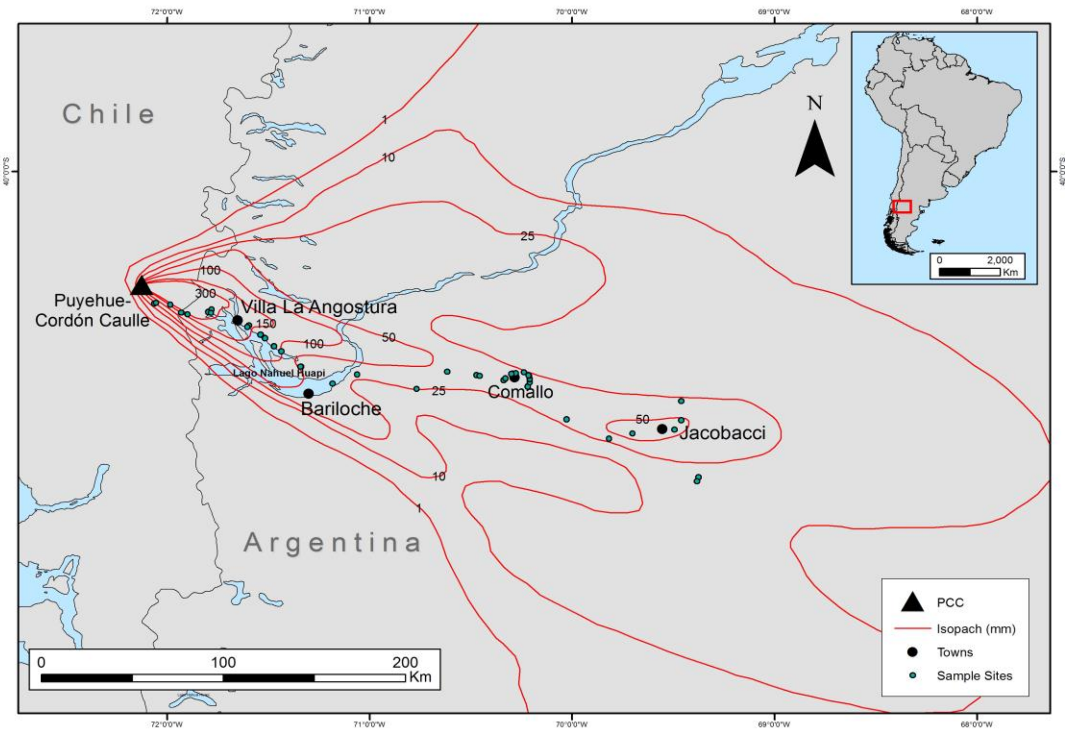


Figure 3.2: Map of the study area showing ash thickness (in mm), main towns visited (black circles), and sites where ash and/or soil samples were taken (blue points), relative to the CC-VC location (black triangle).

The 2011 rhyolitic eruptive sequence was centred on the Cordón Caulle fissure zone (Schipper et al. 2012). The active sequence started on 27 April 2011 when the Observatorio Volcanológico de los Andes del Sur (OVDAS) detected a swarm of volcano-tectonic earthquakes. These earthquakes continued to increase in magnitude and frequency until 4 June 2011 when the eruption sequence began with a series of Plinian style phases (Schipper et al. 2012). A 5 km wide ash and gas plume rose to 12.2 km height. While lava was not initially observed, pyroclastic flows were noted. Ash and gas plumes continued to be released from the fissure with heights up to 13 km, reducing to a few kilometres by early July. Ash plumes continued to be erupted up to 5 km high until early January 2012, with some incandescent explosions visible at night (OVDAS 2011).

The eruption deposited ash over a 75,000 km^2 area to the east (Fig. 3.2). As the CC-VC is located ~18 km from the Chile-Argentina border, most of the area covered by ashfall was in Argentina, including Neuquén, Río Negro and Chubut provinces. Three main population centres received ash deposits. Villa la Angostura, Neuquén, located 54 km ESE from the vent received up to 170 mm of coarse ash; San Carlos de Bariloche located 100 km SE of the vent received 30-45 mm of up to 4 mm sized ash; and Ingenerio Jacobacci, an agricultural service town on the steppe in the eastern part of the province, received 50 mm of fine ash (Collini et al. 2012). The steppe region was also affected by prolonged episodes of poor air quality with high levels of fine airborne ash, due to wind remobilisation of upwind deposits.

3.4 Study Area

The study area contains two distinct agricultural areas: the Nahuel Huapi National Park (within 40 km of the vent, up to 300 mm of ash deposited) and the Jacobacci steppe region (80-220 km from vent, up to 60 mm ash) (Fig. 3.2). Over 90% of the farming in both areas comprises small privately-owned farms, many of which are barely above subsistence level (INTA Bariloche 2012). These two areas are defined by their contrasting environments, climate and farming styles. The Nahuel Huapi National Park is a temperate area that receives up to 1000 mm of precipitation per annum (Servicio Meteorologico Nacional 2012) (Fig. 3.3a & b). The farming system in the area is unique due to its national park status. Farmers are allocated a quota limit of cattle, horses and goats that can be grazed over an allotted parcel of land (up to 100 hectares) (Veblen & Mermoz, 1992). In contrast, the Jacobacci region (Fig. 3.3c & d) is situated on the semi-arid steppe and receives less than 200 mm precipitation per annum. However, in the six years prior to the ashfall, rainfall levels were much lower than this (~160 mm/year) leading to drought conditions in the region (Departamento Provincial de Aguas 2011). Between 200,000 – 300,000 sheep and ~60,000 goats are farmed around Jacobacci, the Comallo Valley and the surrounding steppe area (INTA Bariloche 2012). Prior to the drought, semi-arid conditions limited the most productive grazing land to lowland valleys or mallines, where soil moisture peaks as the groundwater table approaches the surface. Grazing still takes place on the surrounding slopes but at a much lower stocking rate (1-2 animals per hectare, compared with 5 – 6 animals/ha in the malline areas) (J. Escobar, pers comm. 5 March 2012).

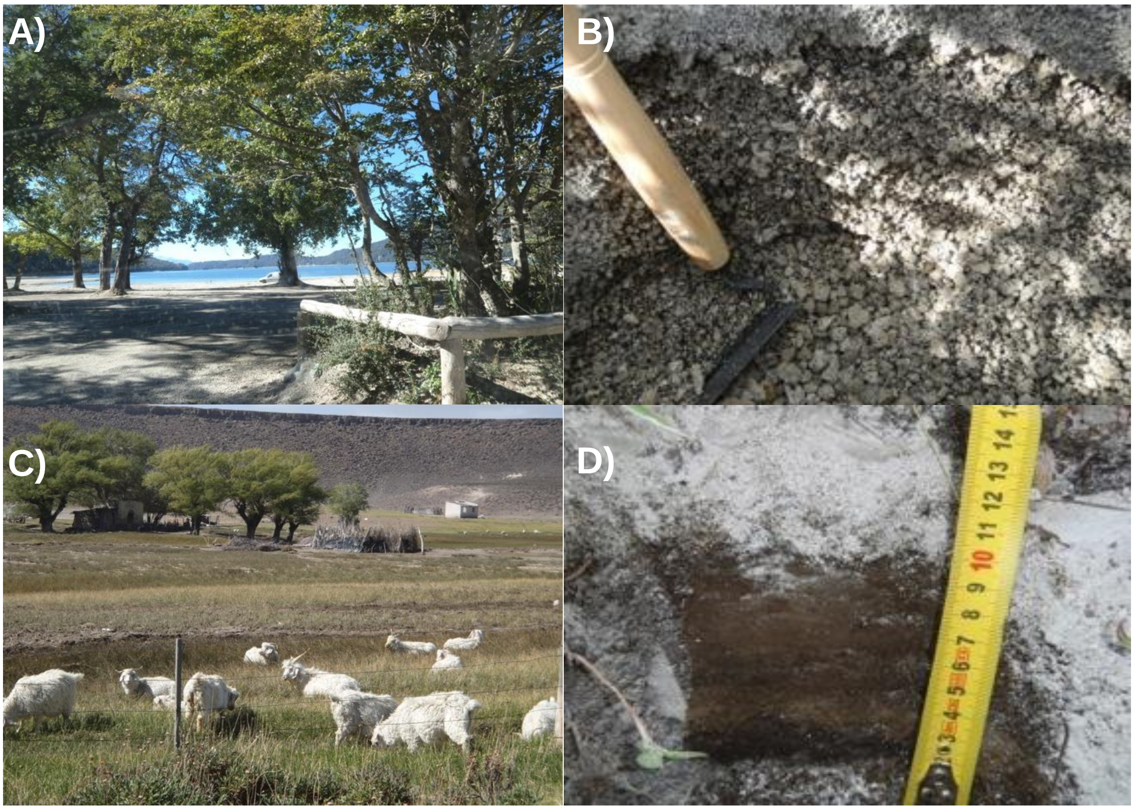


Figure 3.3: Images of the two main agricultural areas located within the study area: A) the Nahuel Huapi National Park area, B) and the deposit it received and C) the Jacobacci/Comallo region, D) and an example of a deposit in the area.

The soil and ash sampling undertaken for this study followed a roughly west-east transect along the main axis of the ashfall area, traversing both of the main agricultural areas affected (Fig. 3.2). Precipitation levels in the depositional region vary widely, with the annual rainfall on the western coast of Chile exceeding 2,000 mm, but on the opposite coast of Argentina rainfall averages less than 200 mm per year (Fig. 3.4). This order of magnitude difference is caused by the "rain shadow" effect, where the predominant westerly flow of air hits the Andes and causes a hyper-humid environment to form; conversely on the downslope side, only dry air arrives, forming a semi-arid environment (Aravena & Luckman 2009; Garreaud et al. 2013; Paruelo et al. 1998). This rainfall gradient influences the soil types seen across the impacted areas. From west to east the dominant soil types in the study area are as follows (using the Food and Agriculture Organisation classification scheme, FAO 1997): lithosols, andisols, cambisols, fluvisols, and yermisols (Table 3.1 & Fig. 3.4).

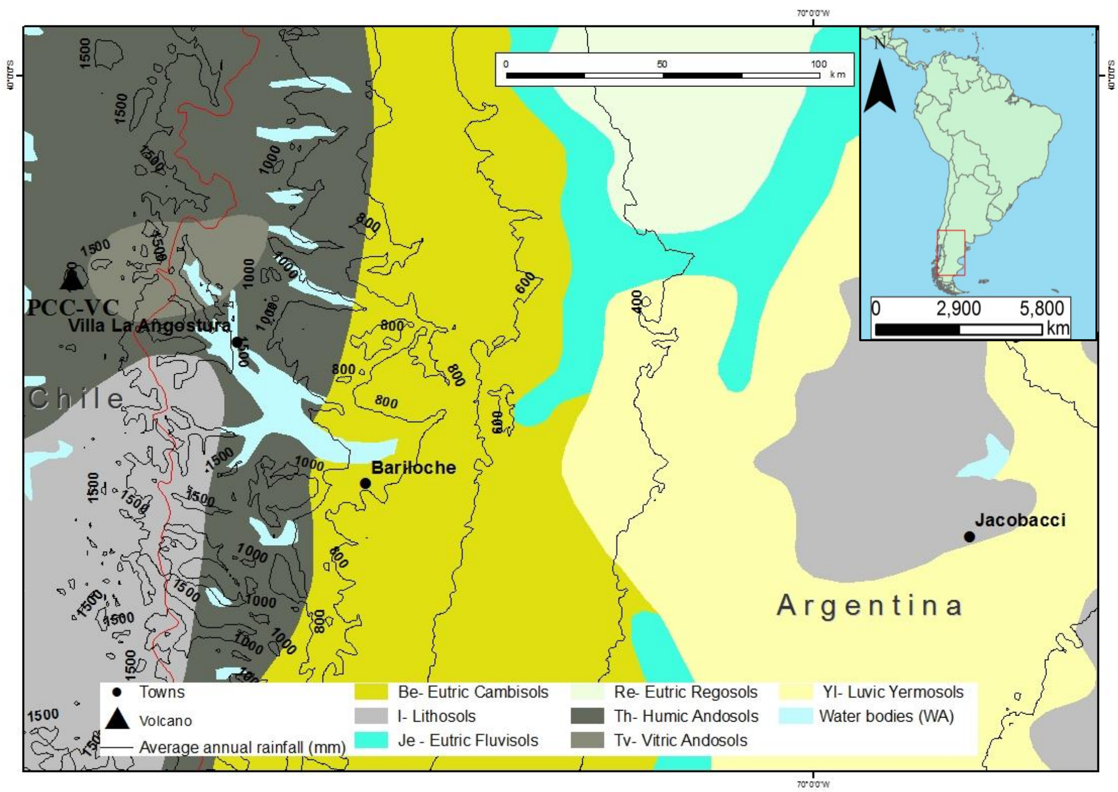


Figure 3.4: Map showing soil types and rainfall isopleths for the study area.

Table 3.1: Soil types found in the area affected by the 2011 CC-VC ashfall events.

Soil type	Description
Lithosols	Found on steep slopes, shallow soils with no soil horizons visible. Made up of mostly un-weathered material.
Andisols	Weathered tephra deposits, dark coloured, and high proportion of glass.
Cambisols	Formed from alluvial, colluvial, and aeolian material, early soil horizons visible, productive soils.
Fluvisols	Young soils composed of alluvial deposits, usually follows path of water bodies, good natural fertility.
Yermisols	Occur in semi-arid to arid environments, low concentration of organic material, prone to cementation and salinization, low fertility.

The soils in the study area generally become less fertile moving eastwards. This restricts the type of farming that can occur. Areas in the temperate Andean zone have the capacity for higher intensity farming, horticultural activities and cattle farming, whereas, farms in the semi-arid steppe are more suited to relatively low intensity, sheep and goat farming.

The Instituto Nacional de Technología Agropecuaria (INTA) estimated that more than a million animals died due to ashfall impacts in the months after the eruption. Losses were most severe in the Jacobacci steppe region (40-60% animal deaths), compared with 20-25% animal losses in the Nahuel Huapi National Park. The difference in losses was likely due to the already marginal conditions in the Jacobacci steppe due to the exceptionally dry conditions, exacerbated by the preceding year's drought (<160 mm of precipitation in the entire year) (Departmento Provincial de Aguas 2014). This left animals and pasture in poor condition, contributing to high levels of losses following the ashfall. A further consequence of the drought was that the area experienced prolonged exposure to windblown remobilised ash, further increasing vulnerability by continuing to contaminate feed and prevent full soil and vegetation recovery. Comparatively low losses occurred in the Nahuel Huapi National Park despite greater ashfall depths received. This is likely due to the free-range nature of the animals making them used to foraging for food, higher availability of non-ash contaminated feed (i.e. low trees and shrubs that were not buried like pasture), and wetter conditions acting to clean vegetation and stabilising ash from wind remobilisation thus preventing recontamination of feed supplies (Wilson et al. 2012).

3.5 Methods

3.5.1 Ash and soil sampling

Immediately following the initial eruption, a series of ash samples were collected along the axis of the ash deposit by G. Villarosa and V. Outes (Fig. 3.2). These samples were collected between 4 and 26 June 2011 and covered multiple phases of the eruption sequence. Eight of these samples, which had undergone minimal rainfall leaching or environmental modification, were sent to the University of Canterbury (Christchurch, New Zealand) for analysis (2011 ash samples; Appendix A.2).

During the February-March 2012 fieldwork campaign, soil and ash samples were collected along the length of the ash plume over a 220 km transect (Fig. 3.2; Appendix A.2). Soil sample sites were preferentially selected in areas that were being actively farmed, with some samples from forestry sites. At each site, four subsamples were collected within a 1 m^2 grid and then composited. Soil samples were collected from beneath the ashfall deposit to the base of the A horizon (typically 150-200 mm depth). In areas where the ash deposit had been cultivated into the upper soil horizon, the combined topsoil material was collected as this represented the active growth medium. Samples of approximately 500 g were taken using a stainless steel hand trowel as an auger, combined and placed in clean, labelled polyethylene bags. Additional information on vegetation cover, agricultural usage and any evidence of irrigation, cultivation and other modifications was also noted. Samples were air dried and transported to New Zealand, where further oven drying to constant weight was completed.

Ash samples were collected at the same locations as the soil samples using a similar grid pattern system. Samples were collected from undisturbed sites using stainless steel cutting tools, taking care to get a total cross-section of the sample but excluding the ash/soil interface. Samples were air-dried and then transported in clean, labelled polyethylene bags. Care was taken to keep disturbance of soil and ash samples to a minimum. Epiclastic samples were identified by the presence of dune structures and cross-bedded internal structure, whereas *in situ* deposits were characterised by flat-lying bedding that draped over the topography (Fig. 3.5). Ash samples will hereafter be referred to as 2011 samples (for fresh ash samples) and 2012 samples (for those taken nine months after the initial eruption).

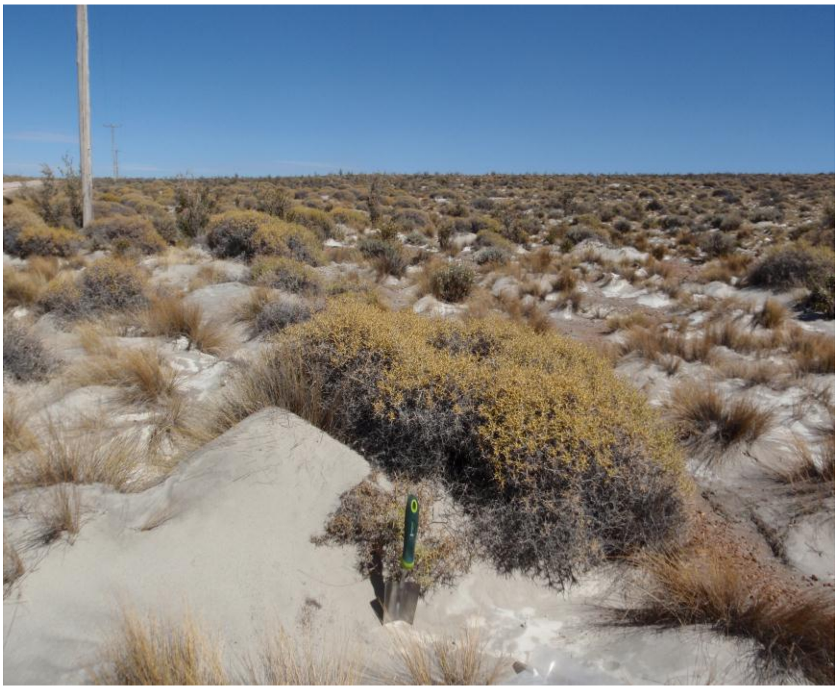


Figure 3.5: Epiclastic ash dune deposits in the Jacobacci area, photographed during field work (hand trowel for scale).

3.5.2 Soil fertility analysis

Soil fertility analyses (pH, Cation Exchange Capacity (CEC) and nutrient concentrations) were undertaken at R.J. Hill Laboratories Ltd (Hamilton, New Zealand). Soil pH was measured using a slurry with a ratio of 1:2 soil:water and potentiometric pH determination (Blakemore et al. 1987). The elements K, Ca, Mg and Na were measured using ammonium acetate extraction (1.0 M, pH 7, 1:20 soil:extractant ratio, 30 minutes contact time) with detection by ICP-OES (Inductively Coupled Plasma – Atomic Emission Spectroscopy) (Metson 1971). Cation Exchange Capacity (CEC) was calculated using the sum of extractable cations and the extractable acidity of the samples (Hesse 1971).

3.5.3 Ash extractions

3.5.3.1 Water-extractable element determinations

Ash analyses were undertaken in accordance with the protocol developed for characterising leachable elements in volcanic ashfall (Stewart et al. 2013). Firstly, a Saturn Digisizer II Laser Sizer was used to determine grain size of the whole sample, then samples were sieved (<2 mm). Ash samples were leached with Milli-Q grade deionised water (<18 MΩ) at a ratio of 1:20 (g ash: mL extractant) for one hour, on an end-over-end shaker. The solution was centrifuged at 2,000 rpm for 5 minutes then filtered through a 0.2 μm cellulose filter.

3.5.3.2 Sequential extractions

In order to perform sequential water extractions, the material removed by filtering was then re-leached with fresh deionised water using the same methods. This leaching process was applied to the same ash sample material two more times to produce an additional second and third leachate solution for testing.

3.5.3.3 Total recoverable metals determinations

Total recoverable metals were determined using a modification of Environmental Protection Agency method 200.8 (Long et al. 1994). One gram of each of the 2011 and 2012 samples was digested with 4 mL 50% HNO_3 and 10 mL 20% HCl at 95 °C for 30 minutes. The samples were cooled, made up to 20 mL with Milli-Q grade water and filtered through 0.2 μm nitrocellulose filter before being diluted with 2% HNO_3 for analysis.

3.5.3.4 Inductively Coupled Mass Spectrometry (ICP-MS & ICP-OES) testing

Ash water leachates and total recoverable solutions were analysed for trace metals using ICP-MS (Agilent 7500 Series) for Al, As, Co, Cr, Cu, Pb and Zn at the University of Canterbury (Christchurch, New Zealand), and ICP-OES (Varian 720) for Ca, Fe, K, Mg, Mn, and Na at Lincoln University (Christchurch, New Zealand). Ion Chromatography (Dionex ICS-2100) was used to determine Cl, F and S (reported as SO_4^{2-}) (University of Canterbury and Hill Laboratories Ltd, Hamilton, New Zealand).

Procedural blanks for all samples and the inclusion of a soil standard reference material (SRM2710, Montana Soil; National Institute of Standards and Technology) for total recoverable metal determinations were used as quality control measures. The average relative percent difference between duplicate leachate samples was less than 23% for all elements, with the majority below 10%. The average relative percent differences for duplicate digest samples were all less than 16%. Detection limits for analysis of water-extractable elements by ICP-MS were (on a dry weight basis): 0.01 mg/kg for As and 0.1 mg/kg for Co, Cu, Mn, Ni, Pb, and Zn. The detection limits for ICP-MS analysis of total digests were: 0.042 mg/kg for As, and 0.42 mg/kg for Co, Cu, Mn, Ni, Pb, and Zn. The ICP-OES detection limits (for water leachates and total digests) were: 5 mg/kg for Ca, Mg, Na, K, Al, and Fe.

In order to assess the differences in the 2011 and 2012 water extractable and total recoverable datasets, Spearmann’s rank correlations and *t-testing* were performed in accordance with standard statistical methods.

3.5.4 Surface water sampling and analysis

Streams in the depositional area of the June 2011 eruption were sampled at various intervals after the eruption. Samples were collected by G. Villarosa and V. Outes between 6-30 June 2011 and by C. Stewart between 1-14 March 2012. Determinations of pH and conductivity were made in the field using a portable meter (Oakton TESTR 35) from Eutech Instruments. Samples were all imported into New Zealand for analysis in accordance with the requirements of the Biosecurity Act 1993. F was determined directly by ion-selective electrode, with a detection limit of 0.05 mg/L. Chloride and sulphate were determined directly by ion chromatography, with detection limits of 0.5 mg/L. Dissolved metals were analysed by ICP-MS at Hill Laboratories (Hamilton, New Zealand) on filtered (to 0.45 μm) samples, with detection limits as follows: As (0.001 mg/L), Al (0.003 mg/L), Cu (0.0005 mg/L, Fe (0.02 mg/L), Mn (0.0005 mg/L) and Pb (0.0001 mg/L). Total metals were determined on unfiltered samples following a nitric acid digestion (APHA Method 3030, modified) with the detection limits as follows: As (0.0011 mg/L), Al (0.0032 mg/L), Cu (0.00053 mg/L), Fe (0.021 mg/L), Mn (0.00053 mg/L) and Pb (0.00011 mg/L).

3.5.5 Gastric leaches

Extractions of the eight ash samples collection in June 2011 were carried out using a simulated gastric leach (0.032 M HCl, adjusted to pH 1.5, at ratios of 1:100 g ash:mL extractant), as per Stewart et al. (2013). Samples were extracted for one hour on an end-over-end mixer, centrifuged, filtered then analysed for F using the ion selective electrode (ISE) method (Massey University, Palmerston North).

3.6 Results & Discussion

3.6.1 Grain size characteristics

Grain size data for ashfall samples is presented in Fig. 3.6a (2011 samples) and 3.6b (2012 samples). No clear relationship between grainsize distribution and distance from the vent is apparent for either year. The June 2011 samples were collected over a period of three weeks, which included multiple eruptive phases, and thus the relationship does not follow the same fining trend that would be expected if the samples had come from a single explosive phase. Samples were also taken at varying distances from the plume axis, further complicating the expected grain size trend. The fining trend is also absent in the 2012 samples (Fig. 3.6b). When considering the 2012 samples, some caution is needed when looking for trends in grain size due to the nine months of exposure to environmental conditions and the unknown quantity of material that remained *in situ* during this time. Grain size analysis is not a key objective of this study, however it is important to assess the grain size characteristics of a deposit before analysing the leachable elements, in order to investigate any association between leachable concentrations and grain size (Stewart et al. 2013). The relationship between increased leachable element concentrations and greater distances from the vent has been demonstrated to occur due in part to the fining effect, as finer grained deposits have greater surface area and longer plume residence times allowing for greater adsorption of soluble salts (Witham et al. 2005). Detailed grain size analysis of the 2011 CC-VC deposit can be found in Bonadonna et al. (2015) and Daga et al. (2014).

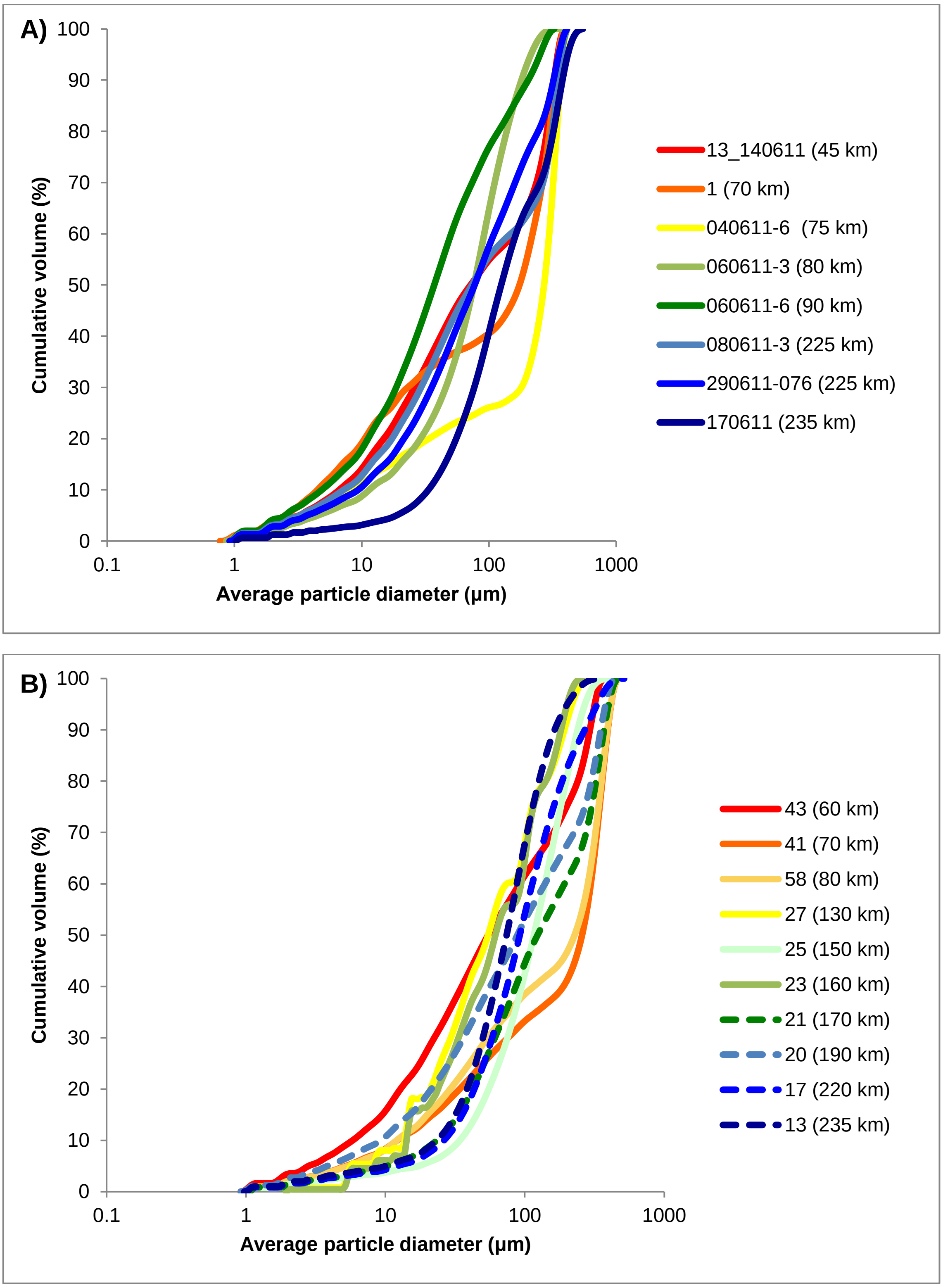


Figure 3.6: Grain size distribution of 2011 (A) and 2012 (B) ash samples, by sample number and distance from vent.

Epiclastic deposits (identified by internal structures, dashed lines in Fig 3.6 b) were found almost exclusively in the dry, windy semi-arid steppe region, including the Jacobacci area (Fig. 3.2 and 3.4) where there was extensive remobilisation of the fall deposit and formation of up to 800 mm tall dunes (Fig. 3.5). The fall deposit in this area was subject to less fluvial erosion and other disturbances (e.g. lower livestock populations). The grain size distribution of the epiclastic deposits does not differ significantly from the *in situ* 2012 deposits (Fig. 3.6b). The grainsize of the CC-VC 2012 epiclastic deposits (50% cumulative volumes of between 73 and 125 μm) is much finer than the remobilised deposits after the 2010 Eyjafjallajokull eruption (50% cumulative volumes between ~450 and 625 μm; Arnalds et al. 2013) and slightly finer than the majority of remobilised deposits sampled in 2008 from the 1991 Hudson eruption (50% cumulative volumes between ~200 and 1250 μm; Wilson et al. 2011b). This fine grain size coupled with the lack of precipitation and the prevailing westerly wind leads to the ongoing, severe wind remobilisation seen in the Argentine steppe area (including the Jacobacci region).

3.6.2 Soil fertility

Volcanic ash is not a desirable growth medium when it is initially deposited. It has no organic material, low Cation Exchange Capacity (CEC) and Olsen P (a measure of phosphorous), and poor basic fertility indicators. In contrast, soils formed from weathered volcanic ash (such as Andisols) are agriculturally useful and provide fertile growth mediums (Shoji et al. 1993). Therefore, it is important to assess soil fertility in the months after an ashfall event to investigate how well the ash deposit is weathering into the soil structure.

During soil sampling in 2012, a noticeable feature was the lack of mixing between the soil and ashfall in the semi-arid area. This is due to the lack of precipitation slowing natural mixing and weathering, and the large-scale, low intensity farming making the costs of mechanical cultivation prohibitive. Mechanical cultivation was also rare in the temperate zone; however, the climatic conditions were more conducive to weathering and the incorporation of the ash deposit into the upper soil horizon.

In order to compare the 2012 results, published pre-eruption results from the impacted area were compiled (Table 3.2). Pre-eruption data shows that soil in Nahuel Huapi National Park had a low CEC for agricultural activity, permitting forestry and small-scale pastoral farming (Table 3.2). However, the Jacobacci steppe region had an elevated CEC and was enriched in major nutrients (P, K, Na, Ca), as would be expected for alkaline soils, but low rainfall permits only low intensity pastoral farming with some horticulture where irrigation water is available. As pre-eruption data were not taken in exactly the same location as the 2012 samples there are limitations in any conclusions drawn.

Table 3.2: Soil fertility measures pre- and post- eruption compared to ideal agricultural values.

	Ideal Agricultural Concentrations*	**Range in soil samples 9 months after eruption**		**Pre-eruption published values^**	
		Temperate	**Semi-Arid**	**Temperate**	**Semi-Arid**
Olsen P (mg/kg)	50 – 100	2 – 8	4 – 17	2-6	16.8-28.2
K (me/100g)	0.5 – 0.8	0.15-0.47	0.17-4.41	0.26-0.54	-
Ca (me/100g)	6 – 12	2.2-8.3	1.9-37.2	5.76- 8.7	-
Mg (me/100g)	1 – 3	0.32-1.96	0.27-11.76	0.43-0.63	-
Na (me/100g)	0.2 – 0.5	0.17-0.43	0.42-14.11	-	-
CEC (me/100g)	25 – 40	5-28	3 – 65	10-30	25.2-35.5

*Brown et al. 2004; Horta & Torrent 2007; Blakemore et al. 1987
^Aruani & Sánchez 2003; Peinemann et al. 1987; Buschiazzo et al. 2009; Mussini et al. 1984.

Ashfall leachates can cause an increase in acidity in soil, however this is usually a short-lived pulse rather than a long term soil fertility issue (Witham et al. 2005). As this study assessed soil fertility nine months after the eruption it is possible that the acidic pulse occurred but was not recorded. Pre-eruption, soil pH was controlled by the climatic zone (Cremona et al. 2011). Temperate zone soils are typically acidic, due to higher rainfall depleting exchangeable base cations (primarily Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) in the soil, coupled with contributions from decaying plant matter contributing organic acids (McLaren and Cameron 1996). Semi-arid soils are typically neutral to alkaline because of the higher proportion of ion-exchange sites occupied by base cations, which also confers buffering capacity (Ugolini and Dahlgren, 2002). Applying this pre-eruption knowledge, any effect on soil pH in the depositional area is not distinguishable from the pre-eruption gradient (Fig. 3.7). It is also relevant to note that the fresh ash leachates were only slightly acidic (pH 6.0-7.0, Table 3.3). Therefore it is likely that even in the initial days and weeks after the eruption the acidic influence of the ash deposit would have been negligible.

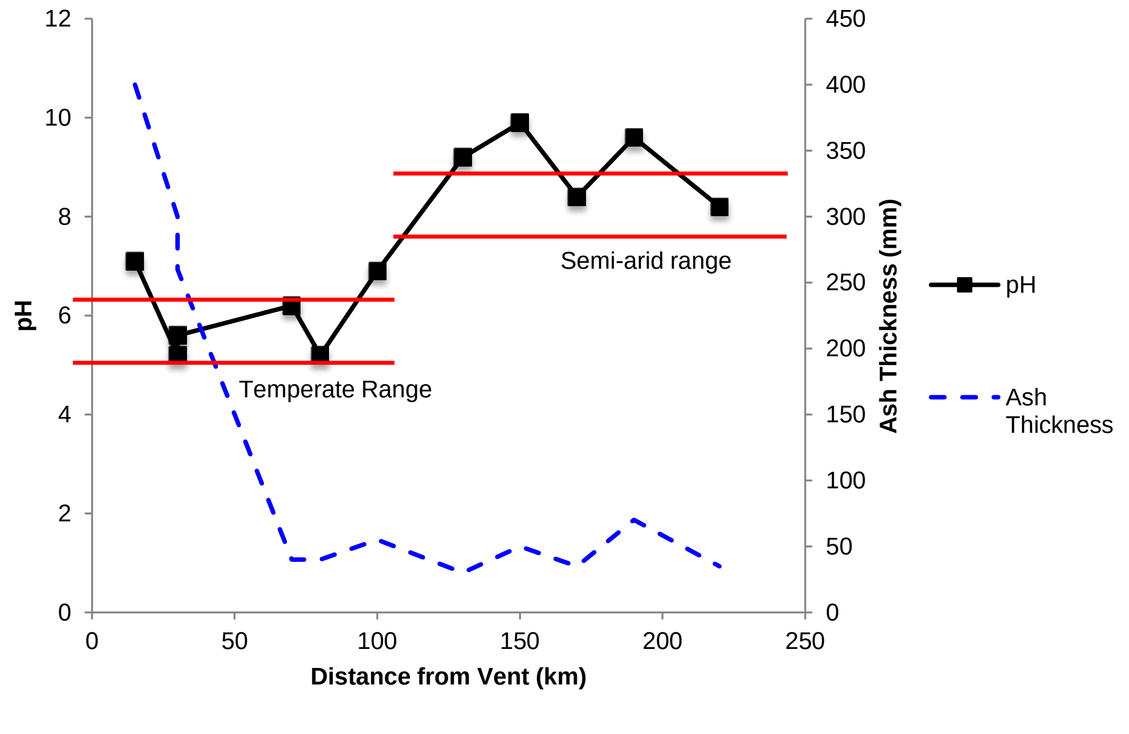


Figure 3.7: Soil pH and ash thickness values across the sampling transect with distance from vent. Normal ranges from McLaren & Cameron 1996).

Volcanic ashfall usually has low CEC values due to the lack of organic and clay matter (Fiantis et al. 2011; Fiantis et al. 2010; Shoji et al. 1993). According to pre-eruption data (Aruani & Sánchez 2003; Buschiazzo et al. 2009; Mussini et al. 1984; Peinemann et al. 1987), soils in the study area exhibit a gradient in CEC, with temperate zone soils having a low-to-medium CEC content (10-30 me/100 g) and semi-arid soils having a high CEC content (25-36 me/100 g) (Table 3.2). The 2012 temperate soil samples have a slightly lower CEC range than the pre-eruption published range. This is likely due to the inclusion of forestry soils in this study, whereas the published ranges focussed solely on pastoral soils, rather than any ashfall influence. Forestry soils characteristically have a lower CEC than those used for pastoral or horticultural farming (White & Hodgson 1999). Post-eruption CEC values in the semi-arid area cover a wide range of values (3-65 me/100g; Table 3.2, Fig. 3.8) due to difference between farms that cultivated ash into the soil (resulting in high CEC values), compared to those farms where the ash deposit remained separate to the soil (low CEC values). The arrows in Fig.

3.8 indicate farms where evidence of cultivation was recorded, it is also likely that fertilisers were applied to the soil in these areas, evidenced by the spike in Ca. Another feature of the semi-arid zone CEC data is the rapid decline at 220 km from the vent. This sample was taken on the edge of Lake Carrilaufquen. This area experienced extremely high on-going wind erosion that has likely led to long-term degradation of soil fertility (Larney et al. 1998). Additionally, the soil was also recorded as sandy in texture which also leads to low CEC values (McLaren & Cameron 1996).

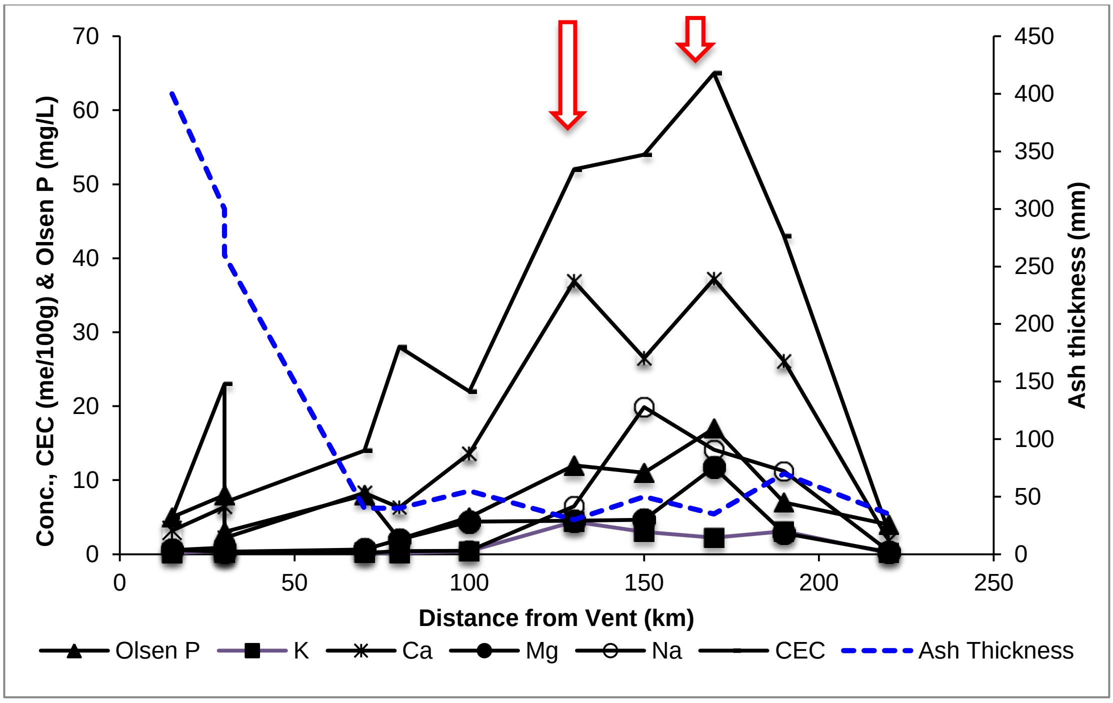


Figure 3.8: Soil fertility parameters and thickness with distance from vent. Arrows indicate sample sites where there was evidence of cultivation and/or irrigation.

To summarise, despite the lack of specific, spatially distributed baseline values, it is likely there was no observable change in soil fertility parameters due to ash deposition in soil samples collected nine months after the initial eruption. This is evidenced by the soil fertility results following trends expected with changing environments and soil types along the transect. Furthermore, across much of the transect (primarily in the semi-arid zone) in the absence of cultivation, there was little evidence of interaction or mixing between the soil and ash deposit, even nine months after deposition. Therefore, due to the lack of long-term impact the ashfall had on soil fertility (either negative or positive), it is assumed that the cultivation of the deposit into the upper soil horizon was the best option to speed up weathering of the deposit and agricultural recovery.

Table 3.3: Sample properties and leachable element concentrations for CC-VC 2011 ash samples at 1:20 water leaches, global median values (from Ayris & Delmelle 2012), and Chaitén leachate results (from Martin et al. 2009 & Durant et al. 2011).

Sample ID	**13_140611**	**1**	**040611-6**	**060611-3**	**060611-6**	**080611-3**	**290611-076**	**170611**	**Global Median**	**Chaiten Average**
Sample state	Dry, fresh	Dry, fresh	Dry, fresh	Dry, fresh	Dry, fresh	Slightly damp	Dry, fresh	Dry, fresh		
Sample collection date	14/06/11	5/06/11	4/06/11	6/06/11	6/06/11	8/06/11	26/06/11	17/06/11		
Land use	Suburban	Forestry	Suburban	Lakeside	Steppe-Temperate	Malline	Malline	Jacobacci		
Distance from Vent (km)	45	70	75	80	90	225	225	235		
Conductivity (µS/cm)	295	NA	258	248	471	177	414	219		
pH	6.1	6.1	6	6.2	6.6	6.5	6.8	7		
Median grain size (um)	71.8	173.7	270.5	76.2	37.1	73.6	77.2	124.8		
Major components (mg/kg)										
Ca	34	33	75	46	88	16	165	59	2140	76
Mg	<5	6	15	8	9	<5	31	6	335	11
Na	142	55	100	79	189	96	125	70	378	56
K	<5	<5	8	<5	5	<5	8	<5	71	19
SO_4	9	<10	53	23	48	8	62	16	1662 (as S)	34
Cl	83	154	193	174	378	130	333	142	1162	208
F	83	12	27	27	167	65	85	67	129	14
Minor components (mg/kg)										
Al	13.0	<5	<5	<5	34.0	<5	<5	<5	58.0	1.9
As	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	0.02	<0.01	0.13	0.3
Co	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.19	0
Cu	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	5	0.03
Fe	<5	<5	<5	<5	<5	<5	<5	<5	21	0.4
Mn	0.2	0.9	0.3	0.9	2.2	0.5	0.2	0.8	20	1.5
Ni	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.5	0.01
Pb	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.11	0
Zn	0.3	0.1	2.4	0.2	0.3	0.5	0.1	0.4	3.6	0.2

3.6.3 Ash surface composition

3.6.3.1 Water-extractable elements in June 2011 ash samples

In general, levels of all water-extractable elements are strikingly low compared to global medians (Table 3.3). The composition of the readily-soluble surface salts is dominated by the elements (in order of decreasing median abundance) Cl, Na, F, Ca, SO_4, Mg and K. Levels of the most abundant (by mass) component (Cl) are a factor of ~6 lower than the global median. A notable feature of the CC-VC ash surface composition is the very low level of water-extractable sulphur (median level of 23 mg/kg SO_4, compared to the global median of 4,986 mg/kg SO_4. This suggests that the CC-VC ash has low potential as a useful source of S for agricultural systems, compared to other eruptions such as the 1995-1996 eruptions of Mt Ruapehu which contained agronomically-useful amounts of available S (3,436-10,016 mg/kg SO_4-S; Cronin et al. 1997; Cronin et al. 1998).

Available F (as fluoride) is generally the component of the greatest toxicological significance in fresh ash (Witham et al. 2005). Although the CC-VC ash has a low overall cargo of soluble salts, levels of F are broadly similar to the global median value of 129 mg/kg, with a median value of 66 mg/kg and a range from 12-167 mg/kg (Table 3.3). Surface composition data for the 2008 eruption of Chaitén volcano, Chile, is also provided for comparison in Table 3.3 as a recent rhyolitic ashfall (recalculated from Durant et al. 2011). With respect to the major components, composition is similar to the CC-VC ash, with the only notable differences being Na (~2 times lower), F (~5 times lower), and K (~2 times higher) in Chaitén ash compared to CC-VC ash.

Water-extractable F showed a significant relationship with median grain size (r_s=-0.671). This negative relationship is due to the increase in leachable elements with smaller grain size due to the greater surface area (Witham et al. 2005). No relationships between levels of water-extractable elements were found with distance from vent or ash loading (approximated from) (Appendix A.3a). This may be due to the ashfall deposit being made up of numerous individual ashfall events (Bonadonna et al. 2015). These comparisons highlight the need for broad spatial coverage when sampling to ensure any compositional variations are fully captured (Ayris et al. 2015).

3.6.3.2 Water-extractable elements in March 2012 ash samples

Levels of water-extractable elements in the ash samples collected in March 2012 are shown in Table 3.4. Concentrations of water-extractable Na, Cl and F were lower overall in 2012 than in 2011 when t-testing for a difference between the two data sets was performed (Appendix A.4). The greatest difference was found for Na (p=0.003,'very significant' difference). No difference was found between 2011 and 2012 data sets for Ca, Mg or SO_4. Comparisons were not made for other elements due to the high proportions of samples with levels below detection limits. However, in all cases, differences between 2011 and 2012 samples became more pronounced when a suspected 'outlier' at site 21 (attributed to fertiliser application at this site) was omitted from the comparison (Appendix A.4).

Trends with distance for water-extractable F and S (as SO_4) are shown in Fig. 3.6 for both the 2011 and 2012 samples. For F levels are highly variable (12-167 mg/kg) in the 2011 samples, collected in the weeks following the 4 June 2011 eruption, with no systematic trend with distance. In contrast, concentrations in the samples collected some nine months later (2012 samples) are lower (1-37 mg/kg) but increase with distance (Fig. 3.9a). Similar, though less pronounced, trends are seen for the other elements including SO_4 (Fig. 3.9b). While the 2011 ash samples showed no systematic trends with distance, concentrations of water-extractable elements in the 2012 ash samples increased with increasing distance from the vent, with the strongest relationship for F (Pearson correlation coefficient r_s =0.933), followed by Ca (r_s =0.812), Na (r_s =0.750) and Cl (r_s =0.771) (Appendix A.3a). Comparisons were not done for other elements due to the high proportion of levels below detection limits. It also must be noted that the same sites were not resampled in 2012, thus, changes over time can cannot be evaluated.

Table 3.4: Sample properties and leachable element concentrations for CC-VC 2012 ash samples at 1:20 water leaches. Global median values (from Ayris & Delmelle 2012) and Chaitén leachate results (from Martin et al. 2009 & Durant et al. 2011) for comparison.

	043a	**41**	**58**	**27**	**25**	**23**	**21**	**20**	**17**	**13**	**Global Median**	**Chaiten Average**
Sample Type	In situ	In situ	In situ	In situ	In situ	In situ	Epiclastic	Epiclastic	Epiclastic	Epiclastic		
Sample Date	11/03/12	11/03/12	13/03/12	6/03/12	6/03/12	6/03/12	6/03/12	6/03/12	6/03/12	4/03/12		
Land Use	Forestry	Pastoral	Pastoral	Melline	Melline	Melline	Melline	Melline	Melline	Steppe		
Distance to Vent (km)	60	70	80	130	150	160	170	190	220	235		
pH	6.4	6.9	6.2	7.1	7.5	8.8	7.5	6.8	8.2	7.2		
Median grain size (um)	108.5	256.9	227.3	54.5	116.2	61.5	123.4	88.5	92.0	74.0		
Major components (mg/kg)												
Ca	8	5	5	32	24	59	154	36	54	42	2140	76
Mg	<5	<5	<5	<5	6	<5	32	10	8	7	335	11
Na	16	27	11	19	20	21	148	63	38	49	378	56
K	6	<5	<5	<5	6	<5	18	5	8	<5	71	19
SO_4	<10	<10	<10	<10	<10	<10	216	12	10	36	1662 (as S)	14
Cl	28	<10	<10	18	34	<10	440	136	64	82	1162	34
F	4	1	3	7	13	8	20	20	22	37	129	208
Minor components (mg/kg)												
Al	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	58	1.9
As	0.01	0.01	<0.01	0.02	0.01	0.04	0.02	<0.01	0.01	<0.01	0.1	0.3
Co	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	0
Cu	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	5	0.03
Fe	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	21	0.4
Mn	9.7	3.2	1.1	2.1	8.7	1.9	2.3	40.2	4.9	30.1	20	1.5
Ni	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.5	0.01
Pb	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.11	0
Zn	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.4	3.6	0.2

An explanation for the increase in F and SO_4 concentrations in the 2012 samples with distance (and therefore with proximity to the semi-arid zone), shown in Fig. 3.9, is that the concentrations of water-extractable elements in the 2012 samples reflect the climate of the depositional area. The greatest loss of elements (leading to very low residual water-extractable levels) occurs in the temperate zone (up to 100 km from the vent) and progressively less leaching of elements in the semi-arid zone consistent with the decreasing rainfall gradient in this area (Fig. 3.4). For example, F levels in ash sampled in the semi-arid zone in 2012 were up to 37 mg/kg. If leachable elements are 'conserved' in arid and semi-arid climates, this may act to prolong the hazard. This effect may be worsened by the occurrence of severe wind-remobilisation in the area.

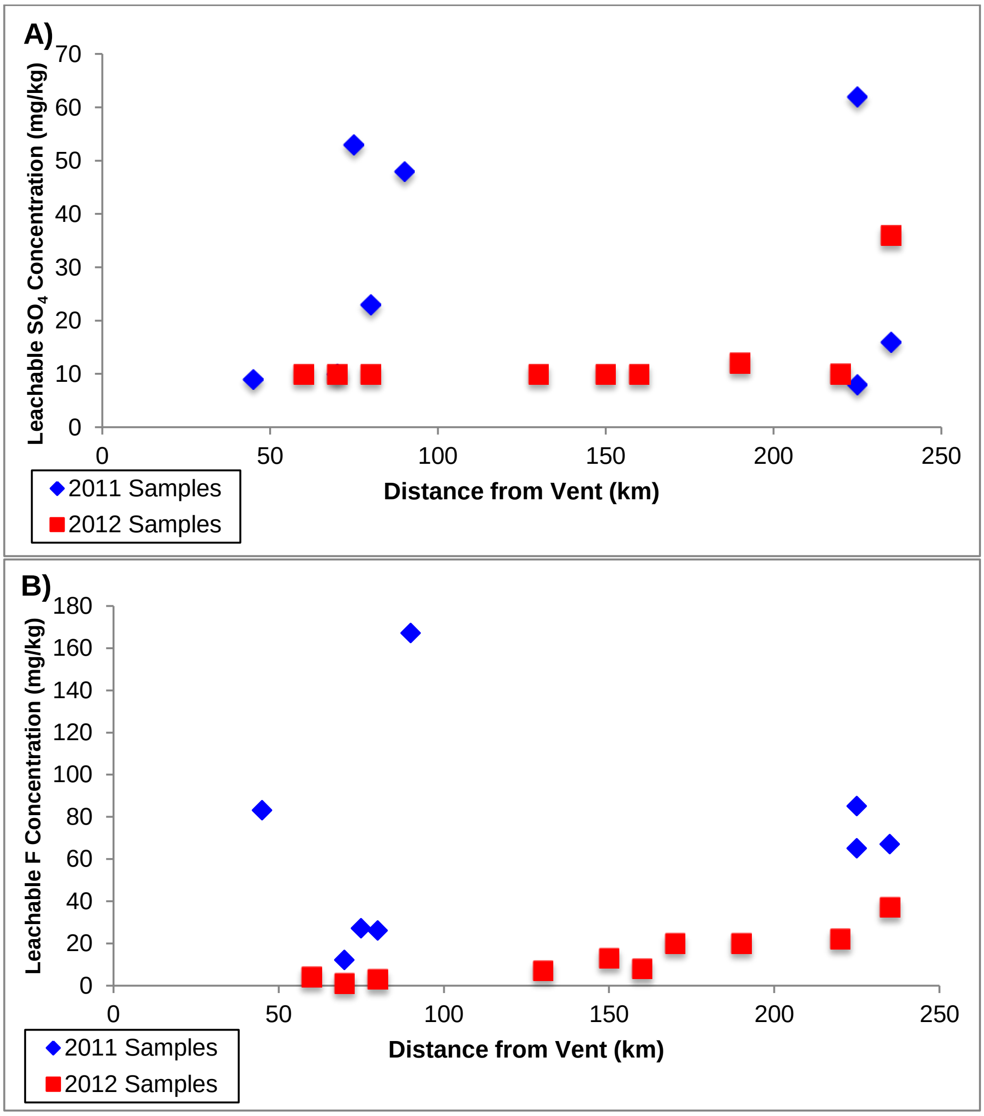
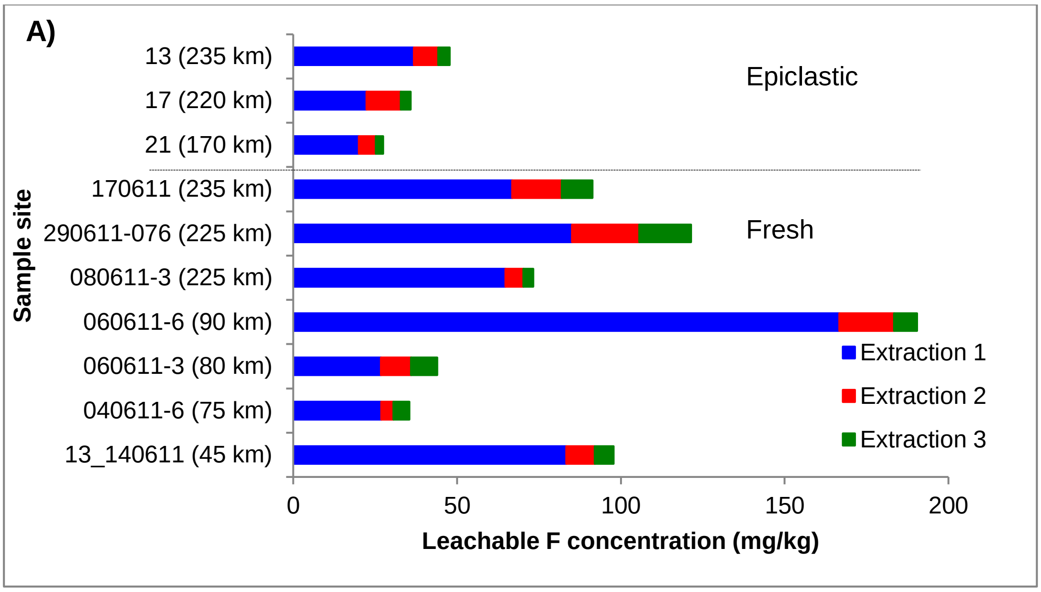


Figure 3.9: A) Comparison of 2011 and 2012 1:20 ash to water leachate F concentrations; B) Comparison of 2011 and 2012 1:20 ash to water leachate SO_4 concentrations.

The 2012 ash samples collected at distances of greater than 170 km from the vent were all epiclastic in nature. It is feasible that the evolution of water extractable elements would be influenced by the remobilisation of deposits, as these epiclastic deposits are affected by different environmental conditions compared to *in situ* deposits. Due to the lack of *in situ* deposits in a comparable area, the influence that this remobilisation had on the water extractable concentrations is unable to be assessed. Quantifying the water extractable concentrations for these deposits is vital as agricultural systems are exposed to prolonged wind remobilisation and resuspension events. During these events they are subjected to repeated exposures to ash containing residual levels of water-extractable elements. In the case of the CC-VC ash, the leachate results (Table 3.4) show that full leaching of the epiclastic ash deposits had not occurred by 2012 due to the semi-arid environment. This result contradicts the theory that the wind remobilisation of ash particles could cause mechanical erosion and reduce the chemical load of the particles. Epiclastic deposits can be finer than the *in situ* deposits (e.g., 1991 Hudson; Wilson et al. 2011b) and a combination of the fine grained nature and suitable environmental conditions (i.e., low precipitation, high wind) cause wind remobilisation (Ayris & Delmelle 2012). The finer grain size can also further contribute to the increased respiratory and ingestion hazard for livestock from wind remobilised ashfall (Wilson et al. 2011a). Fine-grained epiclastic deposits could also possibly contain greater water extractable concentrations (due to the higher surface area and plume residence time of finer grained ash deposits) leading to greater changes in soil fertility and a higher risk of toxicity (Witham et al. 2005). However, in the case of the epiclastic CC-VC the grain size distribution between nearby *in situ* deposits and epiclastic deposits is similar (Fig. 3.6b), therefore, it is likely that the greater concentrations of water extractable elements compared to *in situ* deposits is due to the lack of precipitation leaching.

3.6.3.3 Re-extractions

Previous work suggests that single water extractions may underestimate the environmental availability of agriculturally-important elements such as fluoride and sulphur in some ashes (Cronin et al. 1998; Cronin et al. 2003; Cronin et al. 2014). In the case of F, this is particularly the case for ash generated by phreatomagmatic eruptions through vent-hosted hydrothermal systems which may contain F in slowly-soluble compounds such as CaF_2 and AlF_3. In comparison, purely magmatic eruptions contain F in highly-soluble forms such as NaF. Therefore, the recommendation is to carry out sequential leaches on the same sample for a more complete assessment of the potential of the ash to release F into the environment (Stewart et al. 2013). Re-extractions may also be important for the agronomically-important element S, as very high concentrations may lead to saturation effects occurring in a single leach, particularly at the ratio of 1:20.



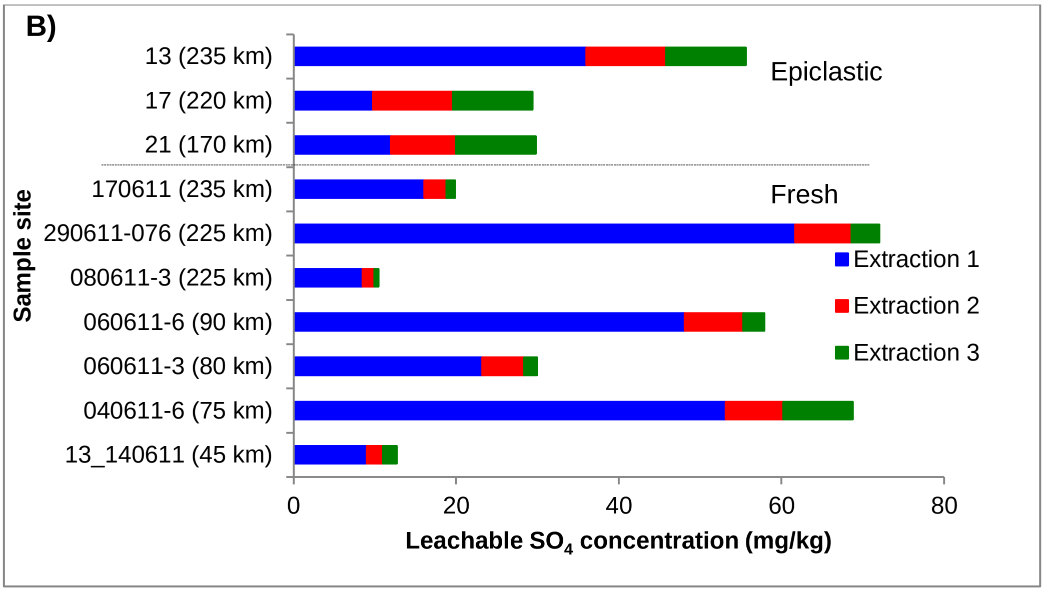


Figure 3.10: A) SO_4 concentrations for sequential 1:20 water extractions of 2011 ash samples and 2012 epiclastic samples. B) F concentrations for sequential 1:20 water extractions of 2011 ash samples and 2012 epiclastic samples. Samples 21, 17 and 13 2012 epiclastic samples, all others 2011 ash samples.

Three sequential leaches were carried out on the 2011 and 2012 epiclastic ash samples (where sample quantities permitted). Re-extractions were carried out only on the 2012 epiclastic deposits as they contained larger amounts of residual S and F than the 2012 *in situ* samples. Results are shown in Fig. 3.10a for F and 3.10b for S (as SO_4). In general, relatively minor additional quantities of both elements are extracted by sequential leaches with deionised water. In the case of F, this is consistent with the June 2011 eruptions of CC-VC being primarily ‘dry’ and magmatic in nature (Cronin et al. 2003). In the case of S, it is probably because the low overall concentrations do not lead to saturation of the initial leachate. Proportions extracted by a single leach (compared to the total of three sequential leaches) did not vary systematically with distance, or with the epiclastic versus fresh nature of the deposit.

3.6.3.4 Total recoverable metals

The total recoverable metal concentrations indicate the maximum possible cumulative inputs of elements released by long-term weathering of ash deposits. Total recoverable element concentrations in the 2011 and 2012 ash samples are elevated by approximately two to three orders of magnitude compared to water-extractable elements (Table 3.5 & 3.6), thus, only ~0.1-1% of the total recoverable elements are water-extractable. For comparison, a suite of total recoverable elements are reported for ash from the 1995 eruption of Mt Ruapehu (Cronin et al. 1997), as this study used similar methods to those used here and total recoverable concentrations are not compiled in the Ayris & Delmelle (2012) review. It may be seen that concentrations of total recoverable elements are generally lower than was the case for the Ruapehu 1995 ash, although individual samples are higher. Calcium, Na, and Al concentrations in the CC-VC ash samples were all around one order of magnitude lower than those from the Ruapehu ashfall, whereas, Fe levels were similar. Potassium levels were depressed compared to the Ruapehu samples (Cronin et al. 1997; Table 3.5).

Table 3.5: Total recoverable metal concentrations for ash digests (modification of EPA Method 200.8) of 2011 ash samples and Ruapehu 1995 ash samples (Cronin et al. 1997).

Sample ID	**13_140611**	**1**	**040611-6**	**060611-3**	**060611-6**	**080611-3**	**290611-076**	**170611**	**Ruapehu ranges**
Sample Type	Dry, fresh	Dry, fresh	Dry, fresh	Dry, fresh	Dry, fresh	Slightly humid	Dry, fresh	Dry, fresh	Dry, fresh
Sample Date	14/06/11	5/06/11	4/06/11	6/06/11	6/06/11	8/06/11	29/06/11	17/06/11	11/10/95-14/10/95
Land Type	Suburban	Forestry	Suburban	Lakeside	Steppe-Temperate	Steppe (Melline)	Steppe (Melline)	Jacobacci	Pasture
Distance to Vent (km)	45	70	75	80	90	225	225	235	15-116
Median grain size (um)	71.8	173.7	270.5	76.2	37.1	73.6	77.2	124.8	
Major components (mg/kg)									
Ca	682	2151	4612	2105	914	763	2604	1294	9546-11918
Mg	116	717	2199	663	222	174	903	287	401-1341
Na	498	513	1006	631	810	785	847	584	2528-3352
K	91	164	276	124	147	150	268	105	506-1390
Minor components (mg/kg)									
Al	4672	2155	4671	2190	974	794	2692	1391	15480-18055
As	0.8	1.2	2.3	0.9	0.9	0.9	1.5	0.7	6.3-<23
Co	1	10	5	2	1	1	2	1	<2.5-<4
Cu	0	94	36	16	7	6	9	8	13.1-24
Fe	2518	4008	4330	15067	3340	2243	2518	3284	4224-9704
Mn	18	51	120	40	23	17	100	21	15.6-1-3
Ni	0.3	0.5	0.7	1.8	0.6	0.4	2.3	0.7	0.63-<4
Pb	1	3	3	2	11	1	9	8	<25
Zn	4	29	21	7	4	3	11	4	5.5-183

Table 3.6: Total recoverable metal concentrations for ash digests (modification of EPA Method 200.8) of 2012 ash samples.

Sample ID	**43**	**41**	**58**	**27**	**25**	**23**	**21**	**20**	**17**	**13**
Sample Type	In situ	In situ	In situ	In situ	In situ	In situ	Epiclastic	Epiclastic	Epiclastic	Epiclastic
Sample Date	11/03/12	11/03/12	13/03/12	6/03/12	6/03/12	6/03/12	6/03/12	6/03/12	6/03/12	4/03/12
Land Use	Forestry	Pastoral	Pastoral	Melline	Melline	Melline	Melline	Melline	Melline	Steppe
Distance to Vent (km)	60	70	80	130	150	160	170	190	220	235
Median grain size (um)	108.5	256.9	227.3	54.5	116.2	61.5	123.4	88.5	92.0	74.0
Major components (mg/kg)										
Ca	1727	1729	1484	2404	2989	1003	1536	1245	2000	1148
Mg	645	550	736	970	86	284	448	292	535	250
Na	567	572	439	735	689	774	605	691	536	463
K	208	168	155	256	175	307	259	242	250	143
Minor components (mg/kg)										
Al	1719	1729	1484	2920	2989	1187	1536	1245	2000	1148
As	1.0	1.0	1.7	1.0	1.1	1.0	1.0	0.9	1.0	0.7
Co	1.4	1.6	1.6	1.6	0.8	1.4	0.9	2.4	1.2	0.6
Cu	13	14	12	8	6	8	4	9	7	5
Fe	2446	2546	2718	3764	3045	1793	2396	1819	2825	1396
Mn	36	36	41	75	48	34	32	28	44	20
Ni	1.7	2.1	1.9	0.5	0.2	0.3	0.2	0.9	1.4	0.2
Pb	1.2	0.8	1.6	0.8	0.9	0.8	0.8	0.7	0.8	0.4
Zn	7	8	7	7	5	7	6	8	6	3

When comparing the recoverable element concentrations and the deposit characteristics that are typically used in risk assessments as measures of hazard intensity, there is a significant correlation with Ca (r_s=0.810), Mg (r_s=0.810), Co (r_s=0.810), Cu (r_s=0.810), and Mn (r_s=0.667) concentrations from the 2011 ash total digests, and median grain size. However, the remaining elements show no correlation with distance from the vent, grain size or ash loading (Appendix A.3c). Few significant correlations were identified when comparing the total recoverable metal concentrations for the 2012 samples. The most significant relationships were between Cu (r_s=-0.783) and Pb (r_s=-0.731) concentrations and distance from vent (Appendix A.3d).

3.6.4 Surface water composition

Release of readily-soluble elements from freshly-fallen ash may lead to concentration increases in surface waters. Changes in water composition for a particular water body depend on the depth of ashfall and its ‘soluble cargo’, the area of the catchment and volume available for dilution, and the pre-existing composition of the water body. Compositional changes in lakes and reservoirs are generally not discernible due to the large volume available for dilution. Changes in streams and rivers have been reported but are typically short-lived.

Due to public concerns about ashfall from the CC-VC eruption contaminating water supplies, health authorities in the area carried out an extensive programme of surface water sampling in relation to regulatory standards for drinking-water in the weeks and months following the eruption. However, as data was reported only in relation to regulatory thresholds, compositional changes could not be determined as most constituents remained below these thresholds both pre- and post-eruption (selected data reported in Wilson et al. 2012). The most problematic effect of the ashfall was increased turbidity levels (due to ash suspended in water) which in turn led to problems for the operation of drinking water treatment systems (Wilson et al. 2012).

Surface water samples were also collected as part of this study. Compositional data is shown in full in Appendices A.5 and A.6. Ideally, sample collection would have focussed on the collection of a high resolution time series at multiple sites, allowing for changes to be followed over time after the eruption in relation to rainfall events. In practice, sampling was limited and opportunistic. Discussion of the data set will be limited here to the elements Cl and F as these were the major water-soluble constituents of the CC-VC ashfall for which there is a reasonably complete data set.

Table 3.7: Trends in pH, conductivity, fluoride and chloride in surface waters sampled in June 2011 with increasing distance from the vent in the CC-VC depositional area.

	Sampling date	**Distance from vent (km)**	**pH**	**Cond (µS/cm)**	**Cl (mg/L)**	**F (mg/L)**
Rio Pireco	22/06/11	35	6.83	58	11.3	0.49
A^{o} Totoral	22/06/11	36	6.7	74	16.6	0.91
Lago Espejo Chico	23/06/11	37	6.7	22	1.4	0.25
A^{o} Espejo Chico	23/06/11	37	7.3	39	1.2	0.2
Rio Ruca Malen	14/06/11	38	7.1	20	1.1	0.13
Rio Pichitraful	23/06/11	44	7.4	51	2.3	0.12
A^{o} Las Piedritas	8/06/11	50	6.7	110	26	1.57
	14/06/11		7	50	8	0.66
A^{o} unnamed	6/06/11	57			4.2	0.32
A^{o} la Estacada	6/06/11	62			3.3	0.35
	8/06/11		6.4	127	21	1.37
	14/06/11		7.1	41	7.4	0.64
A^{o} Ragintuco	6/06/11	64			2.8	0.33
A^{o} Huemul	6/06/11	70			2.4	0.25
	14/06/11		7.4	53	7.6	0.7
A^{o} Cullin Manzano	14/06/11	88	7.55	71	9.4	1.08
Rio Nirihuãu	30/06/11	102	7.76	66	1.1	0.07
A^{o} Comallo	8/06/11	164	8	633	28	1.35
Rio Quetrequile	29/06/11	262	8.1	657	24	1.2

3.6.4.1 Spatial trends

Concentrations of Cl and F, and pH and conductivity, are presented in Table 3.7 for surface water sampled between 6 and 30 June 2011 in the depositional area of the 4 June eruption, listed in order of increasing distance from the vent. The only clear trend with distance is that the two samples collected at the greatest distances from the vent, in the semi-arid area, have markedly higher conductivity and slightly higher pH than the other samples, which were collected in the temperate zone (i.e., within 100 km of the vent). The Rio Nirihuãu sample (102 km from vent) exhibits an intermediate pH. This compositional gradient is likely to be pre-existing and has been attributed to decreasing rainfall away from the Andes (Martin et al. 2009). Surface waters in higher-rainfall areas are highly dilute (low conductivity) and slightly acidic, whereas, in the semi-arid zone they are highly saline (high conductivity) and slightly alkaline.

Fluoride and Cl concentrations were elevated in the distal samples. However, this is most likely associated with the pre-existing compositional gradient. The temperate zone samples showed no trends in F or chloride concentrations with increasing distance from the vent. The lack of a spatial trend with increasing distance from the vent is not surprising as relationships are confounded by sampling being carried out at different time intervals after the eruption. In addition, catchment sizes and flow volumes vary widely, although no information was collected on flow volumes so this influence cannot be accounted for. Nonetheless, a strong positive association exists between F and Cl in this data set ($r=0.941$, $p<0.001$) suggesting that elevated concentrations in the temperate zone samples are due to leaching from the ashfall.

3.6.4.2 Temporal trends

Table 3.8 contains a time series of Cl and F concentrations in water samples collected from four streams at distances of 36-70 km from the vent. For the whole data set a strong positive correlation exists between Cl and F concentrations ($r=0.902$, $p<0.001$) implying a common source. Both elements showed strong ‘spikes’ in concentration following the 4 June 2011 eruption, but were consistently lower when sampled in 2012. As background concentrations of Cl and F for these streams are not known, no comment can be made on whether inputs of leachable elements from the ashfall were continuing. However it seems probable that elevated concentrations of Cl and F at the most-proximal site sampled in 2012 (Arroyo Totoral, 36 km from the vent) are due to continued leaching from the heavy ashfalls recorded in this area (>300 mm ashfall, Table 3.8).

Table 3.8: Chloride and fluoride concentrations (mg/L) in four streams from June 2011 to March 2012 in the CC-VC depositional area.

	Stream sampled (distance from vent)				**Stream sampled (distance from vent)**			
	A° Totoral	**A° Las Piedritas**	**A° La Estacada**	**A° Huemul**	**A° Totoral**	**A° Las Piedritas**	**A° La Estacada**	**A° Huemul**
	36	50	62	70	36	50	62	70
Date sampled	**Chloride (mg/L)**				**Fluoride (mg/L)**			
6-Jun-11			3.3	2.4			0.35	0.25
8-Jun-11		26	21			1.57	1.37	
14-Jun-11		8	7.4	7.6		0.66	0.64	0.7
22-Jun-11	16.6				0.91			
1-Mar-12			7.2	6.6			0.11	0.11
11-Mar-12			5.9	5.6			0.08	0.09
14-Mar-12	9.2	5.6			0.33	0.08		

Risks to livestock drinking water in the temperate zone

Livestock in the temperate zone obtain their drinking-water exclusively from surface waters. In general, the major effects of an ashfall on livestock water supplies are expected to be physical effects such as waterholes being inundated with ash, access to streams restricted by ashfalls which may become saturated and muddy, and the presence of pumice clasts making drinking difficult. Table 3.9 compares the levels of potentially-toxic constituents in surface waters with livestock drinking-water guidelines developed by the Food and Agriculture Organisation (FAO) of the United Nations (Ayers & Westcot 1994). Maximum levels recorded remain below guideline levels set by the FAO. Considering also that 1) these guidelines incorporate wide safety margins (Ayers and Westcot 1994) and 2) that disturbances to water composition are likely to be a short-term phenomenon, it may be concluded that livestock in this region are unlikely to be at additional risk from the ingestion of ash-derived elements in drinking water.

Table 3.9: Comparison of surface water composition in CC-VC ashfall depositional area (temperate zone only) with FAO livestock drinking water guidelines.

	Maximum value recorded[1] (n=17)	**FAO guidelines**
Salinity (µS/cm)[2]	127	1500
Fluoride (mg/L)	1.57	2
Aluminium (mg/L)[3]	1.01	5
Arsenic (mg/L)	0.01	0.2
Copper (mg/L)	0.003	0.5
Iron (mg/L)	0.76	-
Manganese (mg/L)	0.03	0.05
Lead (mg/L)	0.0007	0.1

1. For complete data set refer to Appendices A.5 & A.6.
2. Water with salinity <1500 µs/cm is rated as 'excellent' for livestock uses.
3. Total metal concentrations are reported here for comparability to guidelines.

Risks to livestock drinking water in the semi-arid zone

Relatively high levels of F were recorded in both surface water samples collected in the semi-arid zone (1.2 -1.35 mg/L F). It is probable that these are normal levels for the area as salinity was also very high in these samples, indicating the influence of the rainfall gradient. Municipality staff interviewed in the town of Ingeniero Jacobacci indicated that levels of dissolved constituents in raw water sources (primarily groundwater) are, in general, high and towards the upper range of acceptability for human drinking water. This indicates that livestock in this area are normally subjected to a moderate to high-F environment, especially if forage is irrigated with the same water.

A further source of exposure to F is via contamination of stock drinking water troughs by ashfall. Table 3.10 shows an indicative calculation for a 60-gallon oblong water trough in the Jacobacci region, contaminated with 50 mm ashfall containing 65-85 mg/kg water-extractable F. Predicted concentrations range from 11.1-14.5 mg/L F, assuming that tanks are filled with rainwater rather than groundwater. In practice, tanks in this region are likely to be filled with groundwater which is likely to contain >1 mg/kg F. While these calculations are indicative, they clearly point to the potential for ash contamination of any uncovered water supplies leading to F concentrations well in excess of FAO guidelines.

Table 3.10: Calculations of fluoride concentration in livestock water trough contaminated with 50 mm ashfall in Jacobacci region.

	C_{ash}[1] (mg/kg)	Ash depth (m)	Density[2] (kg/m^3)	A/V[3] (m^2/L)	C_{water}[4,5] (mg/L)
F (low end of range)	65	0.05	700	0.0049	11.1
F (high end of range)	85	0.05	700	0.0049	14.5

1. From Table 2
2. J. Wardman, pers. comm.
3. For tank of length 2 m, width 0.66 m, depth 0.38 m (Hynds 60 gallon oblong protector trough)
4. Assumption that tanks are filled with rainwater (very low F content).
5. C_{water} = C_{ash} (mg/kg)*ash depth (m)*density (kg/m^3)*A/V (m^2/L) (Stewart et al., 2013)

3.6.5 Fluorosis hazard from ash ingestion

Fluoride is known to be the principal element of toxicological importance in volcanic ash leachates, although reported problems from F intoxication following eruptions are relatively rare (Witham et al. 2005). Staff members at the Instituto Nacional de Tecnología Agropecuaria (INTA) were aware of potential fluorosis hazards after volcanic eruptions. For an initial hazard assessment of the Cordón Caulle ashfall, INTA and municipal production managers relied upon data from a single ash sample collected in Bariloche by the Comisión Nacional de Energía Atómica (CNEA, National Atomic Energy Commission) (Hufner & Osuna 2011). The CNEA utilised a standard method for analysing borosilicate glass (ASTM Method C 169-92 Chemical Analysis of Soda-Lime and Borosilicate Glass Volume 15.02), which yielded a result of 0.7 mg/kg F. This method varies from recent methods developed for assessing leachable elements (Stewart et al. 2013) in several important aspects: the ratio of ash to extractant is unspecified; the extraction was carried out at 50°C rather than room temperature; and a colorimetric method was used for detection of F. The CNEA analysis may have underestimated the level of water-extractable F in the 2011 ashfall, as the levels recorded in this study at comparable distances were 27 mg/kg (at 80 km) and 167 mg/kg (at 90 km, Table 3.3).

3.6.5.1 Estimation of bioaccessible F

To provide a more accurate estimation of the bioaccessible fraction of F in ash (and the hazards of ash ingestion), gastric leaches were performed on the 2011 ash using a leaching solution that mimics digestive conditions (simulated gastric fluid, or SGF). Results were inconsistent (Fig. 3.11) in comparison to other studies (e.g. Cronin et al.

2014; Stewart et al., 2014) where SGF-extractable F is consistently higher than water-extractable F, by factors of ~3-5. For the following hazard assessment, maximum and minimum SGF-extractable F values are used for each zone.

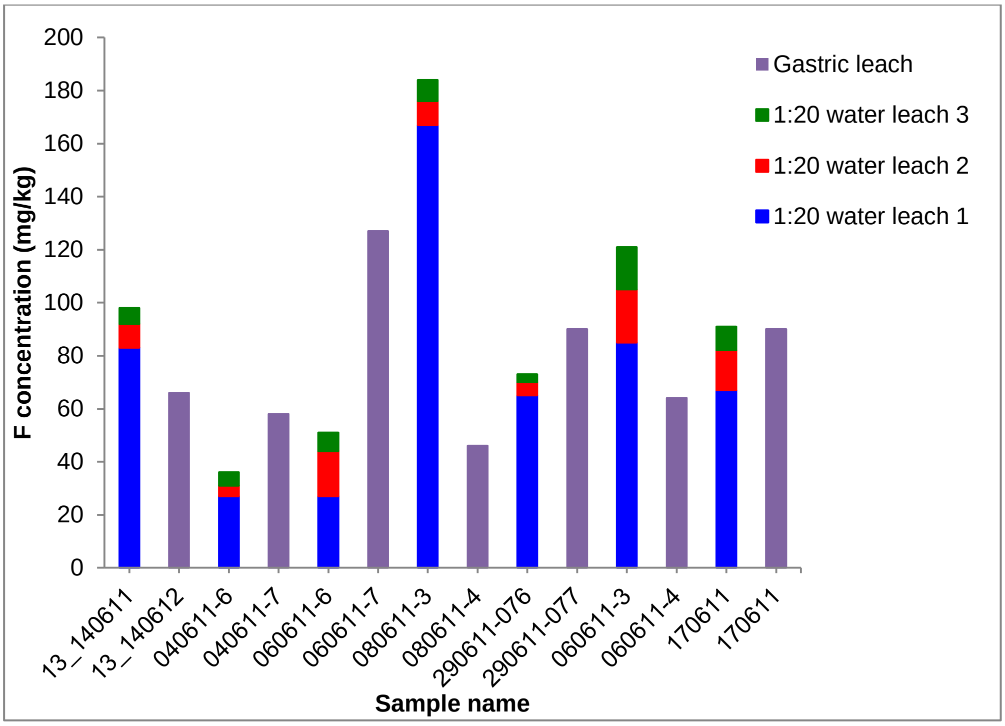


Figure 3.11: Fluoride concentrations from gastric leachates and the three sequential 1:20 water leaches.

3.6.5.2 Acute fluorosis hazard

Toxicity thresholds for F associated with acute exposure (typically defined as a single exposure event or repeated exposures over a duration of less than 24 hours) resulting in acute fluorosis is relatively rare and requires very high doses of F (Livesey and Payne 2011).

In order to evaluate the acute fluorosis hazard to livestock from ingestion of the Cordón Caulle ash, three species of livestock (cattle, sheep and goats) in both optimal and poor condition are considered, for both the temperate and semi-arid climate zones (Table 3.11). For each combination of species and condition, the acutely toxic dose (causing onset of clinical signs of mild acute fluorosis such as gastritis) and lethal dose were calculated based on the animal bodyweight and available toxicity data for F. Then the mass of soil was calculated that would contain that dose of bioaccessible F, using both maximum and minimum concentrations of SGF-extractable F in each climatic zone.

Finally, based on known daily soil ingestion rates, the number of days required to consume the mass of soil containing a toxic dose of F was calculated.

Utilising this approach, it appears unlikely that ingestion of ash from the 2011 eruption could potentially result in acute fluorosis in grazing animals. For the worst case scenario (considering the smallest body mass animals (goats) in poor condition, assuming the highest SGF-extractable F concentration), 55 days of grazing would be required to accumulate an acutely-toxic dose, and this would be very unlikely as small repeated doses are efficiently excreted in urine rather than accumulated (Livesey and Payne 2011).

A limitation of this approach is that it is based only on reported soil ingestion rates. In practice, animals ingest ash coating feed (Araya et al. 1990), and can apparently accumulate large masses in their digestive tracts. However, we are unaware of any available data on ash ingestion rates by livestock to incorporate into these calculations.

3.6.5.3 Chronic fluorosis hazard

Chronic exposure to a toxic substance refers to continuous or repeated exposures over longer periods of time (typically >6 months). Dental fluorosis is the earliest visible sign of chronic fluorosis in mammals (Livesey and Payne 2011). Severe dental fluorosis can cause difficulty in eating. At higher levels of exposure, skeletal fluorosis can cause painful lesions on bones and joints, lameness, osteoporosis and an increased risk of fractures. Direct mortality is rare, but the useful lifespan of the animal is commonly reduced.

Table 3.11: Estimation of the amount of ash to be ingested and the time taken to do so to reach toxic levels in various animals.

Climate and animal type	**Temperate**						**Semi-arid**					
	Cattle		**Sheep**		**Goats**		**Cattle**		**Sheep**		**Goats**	
Animal condition	Optimal	Poor	Optimal	Poor	Optimal	Poor	Optimal	Poor	Optimal	Poor	Optimal	Poor
Average predicted animal weight (kg)	800	550	120	70	40	20	750	450	100	55	40	20
Amount of Fluoride needed to be consumed to be toxic* (g)	48	33	8.4	4.9	2.8	1.4	45	27	7	3.85	2.8	1.4
Amount of Fluoride needed to be consumed to be acutely lethal (g)**	80	55	12	7	4	2	75	45	10	5.5	4	2
Average soil consumption per day^ (g)	1200		275		200		800		180		180	
Minimum fluoride concentration from gastric leach (mg/kg)	58						46					
Amount ingested to reach lethal levels (kg of tephra)	1379.3	948.3	206.9	120.7	69.0	34.5	1630.4	978.3	217.4	119.6	87.0	43.5
Amount ingested to reach toxic levels (kg of tephra)	827.6	569.0	144.8	84.5	48.3	24.1	978.3	587.0	152.2	83.7	60.9	30.4
Approx. area that toxic level tephra would cover^^ (m^2)	55.2	37.9	9.7	5.6	3.2	1.6	195.7	117.4	30.4	16.7	12.2	6.1
Number of days to consume this amount of material	690	474	527	307	241	121	1223	734	845	465	338	169
Maximum fluoride concentration from gastric leach (mg/kg)	127						90					
Amount ingested to reach lethal levels (kg of tephra)	629.9	433.1	94.5	55.1	31.5	15.7	833.3	500.0	111.1	61.1	44.4	22.2
Amount ingested to reach toxic levels (kg of tephra)	378.0	259.8	66.1	38.6	22.0	11.0	500.0	300.0	77.8	42.8	31.1	15.6
Approx. area that toxic level tephra would cover^^ (m^2)	25.2	17.3	4.4	2.6	1.5	0.7	100.0	60.0	15.6	8.6	6.2	3.1
Number of days to consume this amount of material	315	217	241	140	110	55	625	375	432	238	173	86

*Given a toxic (first sign of symptoms of toxicity) dose of ≥70 mg/kg animal weight for sheep and goats and ≥60 mg/kg animal weight for cattle (Cronin et al. 2003)
**Assuming an acutely lethal dose of 100mg/kg of animal weight (Cronin et al. 2003)
^ Healy 1968; Mayland et al. 1975; Vaithiyanathan & Singh 1994
^^Assumed average tephra density of 15kg/m^2 in temperate area and 5kg/m2 in semi-arid area

Factors contributing towards an increased potential for chronic fluorosis in the study area may include:

- The presence of bioavailable F on fresh ashfall (up to 127 mg/kg and 90 mg/kg gastric fluid-extractable F in temperate and semi-arid zones respectively; Fig. 3.11);
- Prolonged exposure period to readily-available F in semi-arid zone, with concentrations of up to 37 mg/kg water-extractable F reported in 2012 ash samples collected ~9 months after the eruption (Table 3.4, Fig. 3.9a)
- Release of F from ashfall into surface waters of the temperate zone (Table 3.7 & 3.8);
- High background levels of F in ground and surface waters of the semi-arid zone (Section 3.5.4.; Edmunds and Smedley 2013).

Several studies from one research group have reported severe chronic fluorosis in populations of wild red deer (Flueck and Smith-Flueck 2013a; 2013b; Flueck 2014) and livestock (Flueck 2013) in the depositional area. Evidence to support this diagnosis includes high rates of F accumulation in bone, and clinical symptoms of dental fluorosis (damaged enamel, rapid wear, pitting, mottling and variable stages of development). The deer populations studied (Flueck and Smith-Flueck 2013a; Flueck 2014) had been monitored annually since 1991, and as clinical fluorosis symptoms were absent before the June 2011 eruption of CC-VC, fluorosis was attributed to the eruption. These authors suggest that, based on rapid post-eruption accumulation of F in bones of wild deer, these animals may be at risk of osteofluorosis. The risk of chronic fluorosis in livestock in the area has been addressed by just one study (Flueck 2013), and its impact on agricultural production has not been well confined. Additionally, it is unknown the influence that chronic fluorosis will have on livestock that already have low productive lifespans irrespective of chronic fluorosis occurring.

3.7 Conclusions

The 2011 CC-VC ashfall had low concentrations of readily-soluble elements compared to other eruptions worldwide, with the exception of F which approached the global median (Ayris & Delmelle 2012). The ashfalls are unlikely to have provided short-term inputs of plant growth nutrients to the soil, whereas previous eruptions have contributed agronomically-useful quantities of sulphur, (e.g., Cronin et al. 1997). We conclude that agricultural losses from the eruption recorded across the region were most likely caused by physical impacts of the ashfalls rather than issues with chemical toxicity. These physical impacts are similar to those recorded following other eruptions and include disruptions to soil processes (impeding gas and water exchange), burial and breakage of vegetation, and impacts on livestock (severe abrasive damage to teeth, starvation caused by smothering of feed and gastrointestinal blockages from ash ingestion) (Arnalds 2013).

Levels of water-extractable F were initially relatively high (up to 167 mg/kg in the 2011 ash samples), indicating the potential for fluorosis hazards. While calculations based on acute fluorosis threshold data indicate that acute fluorosis was unlikely, chronic fluorosis remains a possible consequence, particularly in the semi-arid region where rainfall leaching may be limited. Reports of severe dental fluorosis and F intoxication in both wildlife and livestock in the depositional area (Flueck 2013; Flueck 2014; Flueck & Smith-Flueck 2013a; Flueck & Smith-Flueck 2013b) suggest that continuing exposure to F is occurring.

This study identified that the climate appears to be a dominant influence on post-depositional weathering of ashfall deposits. A feature of the leachable concentrations, the evolution of environmentally-available concentrations after ash deposition, and the soil fertility characteristics, is the two distinct groups of results based on the climatic zone from which samples were taken. As would be expected based on previous studies (Witham et al. 2005), ash samples taken from the semi-arid zone in 2012 demonstrate that only partial leaching of elements had occurred, compared to samples from the temperate zone where leachable concentrations were very low indicating that precipitation leaching in the nine months after the eruption was high. Additionally, severe, on-going wind remobilisation in the semi-arid region also meant that exposure to the ash deposit remained high for many months after the ashfall. This shows that climatic conditions can act to prolong the toxicity hazard. Therefore, the presence of different climatic zones is important to consider when assessing the hazard after an event, and also when disseminating these results into risk information and mitigation advice.

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3.9 References

Alexander, D. (2002). Principles of emergency planning and management. New York: Oxford University Press.

Aravena, J., & Luckman, B. H. (2009). Spatio-temporal rainfall patterns in Southern South America, 2120 (December 2008), 2106–2120. http://doi.org/10.1002/joc

Araya, O., Wittwer, F., Villa, A., & Ducom, C. (1990). Bovine fluorosis following volcanic activity in the southern Andes. Veterinary Record, 126(26), 641–642. Retrieved from http://www.cabdirect.org/abstracts/19902210133.html

Arnalds, O. (2013). The influence of volcanic tephra (ash) on ecosystems. Advances in Agronomy, 121, 331–380.

Arnalds, O., Thorarinsdottir, E. F., Thorsson, J., Waldhauserova, P. D., & Agustsdottir, A. M. (2013). An extreme wind erosion event of the fresh Eyjafjallajökull 2010 volcanic ash. Scientific Reports, 3, 1257. http://doi.org/10.1038/srep01257
Aruani, M. C., & Sánchez, E. E. (2003). Fracciones de micronutrientes en suelos del Alto Valle de Rio Negro, Argentina. Ciencia Del Suelo, 21(2), 78–81.

Ayers, R. S., & Westcot, D. W. (1994). Water quality for agriculture. Rome. Retrieved from http://www.fao.org/docrep/003/t0234e/t0234e00.HTM

Ayris, P. M., & Delmelle, P. (2012). The immediate environmental effects of tephra emission. Bulletin of Volcanology, 74(9), 1905–1936. http://doi.org/10.1007/s00445-012-0654-5

Ayris, P. M., Delmelle, P., Pereira, B., Maters, E. C., Damby, D. E., Durant, A. J., & Dingwell, D. B. (2015). Spatial analysis of Mount St. Helens tephra leachate compositions: implications for future sampling strategies. Bulletin of Volcanology, 77(7), 60. http://doi.org/10.1007/s00445-015-0945-8

Blakemore, L. C., Searle, P. L., & Daly, B. K. (1987). Methods for chemical analysis of soils. New Zealand Soil Science Bureau, Wellington.

Bonadonna, C., Cioni, R., Pistolesi, M., Elissondo, M., & Baumann, V. (2015). Sedimentation of long-lasting wind-affected volcanic plumes : the example of the 2011 rhyolitic Cordón Caulle eruption, Chile. Bulletin of Volcanology, 77(13). http://doi.org/10.1007/s00445-015-0900-8

Buschiazzo, D. E., Panebianco, J. E., Guevara, G., Rojas, J., Zurita, J. J., Bran, D., & Hurtado, P. (2009). Incidencia potencial de la erosión eólica sobre la degradación del suelo y la calidad del aire en distintas regiones de la argentina. Ciencia Del Suelo, 27(2), 255–260.

Buteler, M., Stadler, T., López, G. P., Lassa, M. S., Liaudat, D. T., & Fernandez-arhex, D. A. V. (2011). Propiedades insecticidas de la ceniza del complejo volcánico Puyehue-

Cordón Caulle y su posible impacto ambiental. Revista de la Sociedad Entomológica Argentina, 70(3-4), 149–156.

Buzea, C., Pacheco, I. I., & Robbie, K. (2007). Nanomaterials and nanoparticles: sources and toxicity. Biointerphases, 2(4), MR17–R71. http://doi.org/10.1116/1.2815690

Collini, E., Osores, M. S., Folch, A., Viramonte, J. G., Villarosa, G., & Salmuni, G. (2012). Volcanic ash forecast during the June 2011 Cordón Caulle eruption. Natural Hazards, (June 2011). http://doi.org/10.1007/s11069-012-0492-y

Cook, R. J., Barron, J. C., Papendick, R. I., & Williams, G. J. (1981). Impact on agriculture of the Mount St. Helens eruptions. Science (New York, N.Y.), 211(4477), 16–22. http://doi.org/10.1126/science.211.4477.16

Cremona, V., Ferrari, J., & Lopez, S. (2011). La cenizas volcanicas y los suelos de la region. Bariloche.

Cronin, S. J., Hedley, M. J., Neall, V. E., & Smith, R. G. (1998). Agronomic impact of tephra fallout from the 1995 and 1996 Ruapehu Volcano eruptions , New Zealand. Environmental Geology, 34(April), 21–30.

Cronin, S. J., Hedley, M. J., Smith, R. G., & Neall, V. E. (1997). Impact of Ruapehu ash fall on soil and pasture nutrient status 1. October 1995 eruptions. New Zealand Journal of Agricultural Research, 40(3), 383–395. http://doi.org/10.1080/00288233.1997.9513260

Cronin, S. J., Hedley, M. J., Smith, R. J., & Neall, V. E. (1997). Impact of Ruapehu ash fall on soil and pasture nutrient status 1 October 1995 eruptions. New Zealand Journal of Agricultural Research, 40(January), 383–395.

Cronin, S. J., Neall, V. E., Lecointre, J. A., Hedley, M. J., & Loganathan, P. (2003). Environmental hazards of Fluoride in volcanic ash : a case study from Ruapehu volcano, New Zealand. Journal of Volcanology and Geothermal Research, 121(3-4), 271-291.

Cronin, S. J., Stewart, C., Zernack, V., Brenna, M., Procter, J. N., Pardo, N., Irwin, M. (2014). Volcanic ash leachate compositions and assessment of health and agricultural hazards from 2012 hydrothermal eruptions, Tongariro, New Zealand. Journal of Volcanology and Geothermal Research. http://doi.org/10.1016/j.jvolgeores.2014.07.002

Daga, R., Ribeiro Guevara, S., Poire, D. G., & Arribére, M. (2014). Characterization of tephras dispersed by the recent eruptions of volcanoes Calbuco (1961), Chaitén (2008) and Cordón Caulle Complex (1960 and 2011), in Northern Patagonia. Journal of South American Earth Sciences, 49, 1–14. http://doi.org/10.1016/j.jsames.2013.10.006

Departamento Provincial de Aguas. (2011). Análisis de Registros Pluviométrico – Estación Jacobacci.

Departmento Provincial de Aguas. (2014). Analisis de registros pluviometrico - Estacion Jacobacci. Retrieved from http://dpa.gov.ar/clima/informes/jacobacci.pdf

FAO. (1997). Soil map of the world. Revised legend, with corrections and updates. Roma.

Fiantis, D., Nelson, M., Shamshuddin, J., Goh, T. B., & Van Ranst, E. (2010). Leaching experiments in recent tephra deposits from Talang volcano (West Sumatra), Indonesia. Geoderma, 156(3-4), 161–172. http://doi.org/10.1016/j.geoderma.2010.02.013

Fiantis, D., Nelson, M., Shamshuddin, J., Goh, T. B., & Van Ranst, E. (2011). Changes in the Chemical and Mineralogical Properties of Mt. Talang Volcanic Ash in West Sumatra during the Initial Weathering Phase. Communications in Soil Science and Plant Analysis, 42(5), 569–585. http://doi.org/10.1080/00103624.2011.546928

Flueck, W. (2013a). Effects of fluoride intoxication on teeth of livestock due to recent volcanic eruption in Patagonia, Argentina. Online Journal of Veterinary Research, 14(4), 167–176. Retrieved from http://www.deerlab.org/Publ/pdfs/68.pdf

Flueck, W. T. (2013b). Effects of fluoride intoxication on teeth of livestock due to a recent volcanic eruption in eruption in Patagonia, Argentina. Online Journal of Veterinary Research, 17(4), 167–176.

Flueck, W. T. (2014). Continuing impacts on red deer from a volcanic eruption in 2011. European Journal of Wildlife Research. http://doi.org/10.1007/s10344-014-0828-x

Flueck, W. T., & Smith-Flueck, J. A. M. (2013a). Severe dental fluorosis in juvenile deer linked to a recent volcanic eruption in Patagonia. Journal of Wildlife Diseases, 49(2), 355–66. http://doi.org/10.7589/2012-11-272

Flueck, W. T., & Smith-Flueck, J. A. M. (2013b). Temporal kinetics of fluoride accumulation: from fetal to adult deer. European Journal of Wildlife Research, 59(6), 899–903. http://doi.org/10.1007/s10344-013-0734-7

Francis, P. (1976). Volcanoes (1st ed.). Great Britain: Penguin Books.

Garreaud, R., Lopez, P., Minvielle, M., & Rojas, M. (2013). Large-Scale Control on the Patagonian Climate. Journal of Climate, 26(1), 215–230. http://doi.org/10.1175/JCLI-D-12-00001.1

Hesse, P. R. (1971). A textbook of soil chemical analysis. London: John Murray.
Hufner, R., & Osuna, C. M. (2011). Characterisation de muestras de cenizas volcanicas volcan Puyehue.

INTA Bariloche. (2012). Análisis económico-productivo de la región afectada por la caída de cenizas del cordón Caulle-Puyehue, en la provincia de Río Negro.

ISDR (2009). 2009 UNISDR Terminology on Disaster Risk Reduction. Geneva, Switzerland.

Larney, F. J., Bullock, M. S., Janzen, H. H., Ellert, B. H., & Olson, E. C. S. (1998). Wind erosion effects on nutrient redistribution and soil productivity. Journal of Soil and Water Conservation, 53(2), 133–140.

Long, S. E., Martin, T. D., & Martin, E. R. (1994). Determination of trace elements in water and wastes by inductively coupled palsma - mass spectrometry (Vol. 4). Cincinnati, Ohio.

Martin, R. S., Watt, S. F. L., Pyle, D. M., Mather, T., Matthews, N. E., Georg, R. B., Day, J. A., Fairhead, T., Witt, M. L. I., & Quayle, B. M. (2009). Environmental effects of ashfall in Argentina from the 2008 Chaitén volcanic eruption. Journal of Volcanology and Geothermal Research, 184(3-4), 462–472. http://doi.org/10.1016/j.jvolgeores.2009.04.010

McLaren, R. G., & Cameron, K. C. (1996). Soil Science. Melbourne: Oxford University Press.

Metson, A. J. (1971). Methods for chemical analysis for soil survey samples. Wellington.

Mussini, E., Crespo, G., & Bianco, H. (1984). Evolucion de la materia organica en suelos de la provinca del Neuquen. Ciencia Del Suelo, 2(1).

Paruelo, J. M., Beltran, A., Jobbagy, E., Sala, O. E., & Golluscio, R. A. (1998). The climate of Patagonia: general patterns an controls on biotic processes. Ecologia Austral, 8(1), 85–101.

Peinemann, N., Andreoli, A. Y., & Sanchez, E. E. (1987). Fracciones y dinamica del fosforo y potasio en suelos del Alto Valle del Rio Negro. Ciencia Del Suelo, 5(1), 9–18.

Rubin, C. H., Noji, E. K., Seligman, P. J., Holtz, J. L., Grande, J., & Vittani, F. (1994). Evaluating a fluorosis hazard after a volcanic eruption. Archives of Environmental Health, 49(5), 395–401. http://doi.org/10.1080/00039896.1994.9954992

Schipper, C. I., Tuffen, H., & Castro, J. M. (2012). Shallow vent architecture of Puyehue Cordón-Caulle , as revealed by direct observation of explosive activity. Geophysical Research Abstracts, 14(1).

Shoji, S., Nanzyo, M., & Dahlgren, R. A. (1993). Volcanic Ash Soil. Amsterdam: Elsevier Science.

Singer, B. S., Jicha, B. R., Harper, M., Naranjo, J., Lara, L. E., & Moreno-Roa, H. (2008). Eruptive history, geochronology, and magmatic evolution of the Puyehue-Cordon Caulle volcanic complex, Chile. Geological Society of America Bulletin, 120(5-6), 599–618. http://doi.org/10.1130/B26276.1

Smithsonian. (2014). Puyehue-Cordon Caulle Weekly Reports. Retrieved January 5, 2014, from http://www.volcano.si.edu/world/volcano.cfm?vnum=1507-15=

Southern Andes Volcanic Observatory. (2011). Volcanic Activity Reports 2011/12. Retrieved January 5, 2012, from http://www2.sernageomin.cl/ovdas/ovdas7/informativos2/informes_ovdas01.php

Stewart, C., Horwell, C., Plumlee, G., Cronin, S., Delmelle, P., Baxter, P., Calkins, J., Damby, D., Morman, S., & Oppenheimer, C. (2013). Protocol for analysis of volcanic ash samples for assessment of hazards from leachable elements. Method developed by the International Volcanic Health Hazard Network and ratified by IAVCEI. http://www.ivhhn.org/images/pdf/volcanic_ash_leachate_protocols.pdf

Stewart, C., Cronin, S.J., Wilson, T. and Clegg, S. (2014) Analysis of Mt Sinabung ash: implications for animal health. GNS Science Report 2014-65.

Thorarinsson, S. B., & Sigvaldason, G. E. (1971). The Hekla eruption of 1970. Bulletin of Volcanology, 36(2), 269–288.

Veblen, T., & Mermoz, M. (1992). Ecological impacts of introduced animals in Nahuel Huapi Animals Park, Argentina. Conservation Biology, 6(1), 71–83. Retrieved from http://onlinelibrary.wiley.com/doi/10.1046/j.1523-1739.1992.610071.x/abstract

White, J., & Hodgson, J. (1999). New Zealand pasture and crop science. Auckland: Oxford University Press.

Wilson, T., Cole, J., Cronin, S., Stewart, C., & Johnston, D. (2011a). Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: lessons for recovery. Natural Hazards, 57(2), 185–212. http://doi.org/10.1007/s11069-010-9604-8

Wilson, T., Cronin, S., Cole, J., & Johnston, D. (2009). Impacts and rehabilitation of pasture following volcanic ashfall. In Vulnerability of pastoral farming systems to volcanic ashfall hazards (pp. 71–126). PhD Thesis.

Wilson, T. M., Cole, J. W., Stewart, C., Cronin, S. J., & Johnston, D. M. (2011b). Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. Bulletin of Volcanology, 73, 223–239. http://doi.org/10.1007/s00445-010-0396-1

Wilson, T., Stewart, C., Bickerton, H., Baxter, P., Outes, V., Villarosa, G., & Rovere, E. (2012). The health and environmental impacts of the June 2011 Puyehue-Cordón Caulle volcanic complex eruption: a report on the findings of a multidisciplinary team. GNS Science report 2012/20.

Witham, C., Oppenheimer, C., & Horwell, C. (2005). Volcanic ash-leachates: a review and recommendations for sampling methods. Journal of Volcanology and Geothermal Research, 141(3-4), 299–326. http://doi.org/10.1016/j.jvolgeores.2004.11.010

Chapter Four
Agricultural impact assessment and management after three widespread tephra falls in Patagonia, South America

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4.1 Abstract

Agricultural production is often concentrated in volcanically active areas where weathered volcanic products form fertile soils. However, this proximity means agriculture is exposed to tephra fall hazards. The type and severity of impacts to agricultural systems from tephra fall are dependent on both the hazard intensity metrics (tephra fall characteristics, such as thickness, grain size, etc.), and the vulnerability characteristics of the exposed agricultural system(s). Understanding the relationship between significant intensity metrics of tephra fall hazard and farm-scale and region-scale vulnerabilities is key to impact assessment and informing management and recovery strategies. Several large silicic eruptions have occurred over the past 20 years in the Patagonian region of South America; the 1991 Hudson, 2008 Chaitén, and 2011 Cordón Caulle eruptions. These events deposited varying thicknesses of tephra on thousands of farms distributed across a variety of climates and production styles.

Drawing on impact assessment data collected from interviews undertaken on short post-event impact assessment (post-EIA) reconnaissance trips, and other reports, this study evaluates the importance of tephra thickness as a hazard intensity metric (HIM), and vulnerability characteristics (VC) when assessing impacts in the short and long term, and compares the effectiveness of response, and recovery strategies. Whilst tephra thickness was the best single indicator of agricultural production losses, other factors, notably climate, farm type, and access to mitigation measures such as irrigation and/or cultivation, were also important indicators of damage. The climatic zone and associated precipitation level was found to be one of the most important characteristics of vulnerability, with higher damage occurring at lower tephra thicknesses in the semi-arid regions compared to farms in the temperate zone.

4.2 Introduction

Global population growth places increasing pressures on maintaining and increasing food production from agricultural systems (Godfray et al. 2010). Production is often concentrated in volcanically active areas where weathered volcanic products form fertile soils (Shoji et al. 1993). Tephra fall is one of the most common hazards from an explosive volcanic eruption and can cover thousands of square kilometres of agricultural land, potentially reducing agricultural production (Blong, 1984). Tephra fall can have both direct (i.e., physical and chemical effects to crops, livestock and soils, Table 4.1) and indirect effects to agricultural production (i.e. due to disruption of electricity supply, transport networks and water supplies) (Neild et al. 1998; Wilson & Cole, 2007). The high exposure and potential consequences of tephra fall for agriculture means that an understanding of the impacts that can occur, and their likelihood, magnitude and duration is vital to managing the risk.

Risk and impact assessments (terminology is defined in Table 4.2) are approaches that can deterministically or probabilistically forecast potential consequences, depending on the desired outcome. They can be used to inform the development of risk mitigation and preparedness strategies before an eruption and inform damage assessment, emergency response and recovery strategies after an eruption occurs to minimise agricultural losses. In the case of volcanic hazards, risk and impact assessment is a rapidly developing field but there are few fully developed open-source models available (Sparks et al. 2013). There have been considerable advances in tephra fall hazard modelling occurring over the past two decades (Bonadonna, 2005; Jenkins et al. 2012) and tephra fall impacts to agriculture are also largely known and their causes well constrained qualitatively (Cronin et al. 1998; Wilson et al. 2011; Jenkins et al. 2014a; Jenkins et al. 2014b). However, there has been less progress on developing fully integrated tephra impact and quantitative risk models for agriculture which relate hazard intensity to impact, with a key constraint being the lack of quality impact and vulnerability data (Jenkins et al. 2014a; Wilson et al. 2009). Several studies have presented models which relate tephra fall thickness or load (kg/m^2) to agriculture impacts. These are informed by post-event impact assessments (post-EIA) observations and expert judgment (Blong, 1984; Wilson & Kaye, 2007; Jenkins et al. 2014b). Such studies all acknowledge they are relatively simplistic and are based on small samples of empirical data. Post-event impact assessments (Sword-Daniels et al. 2011; Wardman et al. 2012; Wilson et al. 2007; Wilson et al. 2011a; Wilson et al. 2012) and empirical laboratory studies (Cronin et al. 1998; Wilson 2009) have been used to fill this void (Wilson et al. 2011; Wilson et al. 2014; Jenkins et al. 2014a; Jenkins et al. 2014b).

Table 4.1: Expected physical and chemical impacts to soil, vegetation and animal health at A) thin (0-10 mm); B) moderate to thick (10-500 mm); and C) very thick (>500 mm) tephra fall depths.

A) Thin ashfalls (0-10 mm)

	Physical Impacts	**Examples and References**	**Chemical Impacts**	**Examples and References**
Soil	Tephra permeability can influence soil gas and water exchange.	Lanzarote (Diaz et al. 2005); Mt St Helens (Cook et al. 1981)	Increasing soil acidity due to tephra leachates, usually minor and/or short-term.	Mt. St Helens (Dahlgren et al. 1999; Sneva et al. 1982); Kasatochi Island (Wang et al. 2010); Popocatepétl (Armienta et al. 2011) Others (Ayris & Delmelle, 2012; Ugolini & Dahlgren, 2002; Zheng, 2010)
	Cementation of tephra can further reduce water infiltration and gas exchange.	Hudson (Wilson et al. 2011b); Puyehue-Cordón Caulle (Wilson et al. 2012b); Mt. St Helens (Cook et al. 1981)	Can add beneficial amounts of some elements in some cases (where a deficiency is present) – particularly sulphur and potassium.	Ruapehu (Cronin et al. 1997; Cronin et al. 1998; Johnston et al. 2000); Fuego and El Chichón (Varekamp et al. 1984; Veneklaas, 1990)
	Radiation can be reflected lowering the soil temperature.	Mt. St Helens (Cook et al. 1981); Others (Ayris & Delmelle, 2012; Smith et al., 2010)	Addition of elements from environmentally-available soluble salts coating tephra and more slowly soluble elements, such as fluoride, aluminium and chloride	Review paper (Ayris & Delmelle, 2012)
Vegetation	Photosynthesis prevented due to covering of leaves with tephra. Abrasion of vegetation due to tephra particles (primary and remobilised).	Merapi (Wilson et al. 2007); Mt. St Helens (Antos & Zobel, 1985; Cook et al. 1981; Dale et al. 2005; Seymour et al. 1983; Sneva et al. 1982); Hudson (Wilson et al. 2011a) ; Puyehue-Cordón Caulle (Wilson et al. 2012b)	Chemical burns to leaves and fruits due the acidity of tephra.	Merapi (Wilson et al. 2007); Mt. St Helens (Cook et al. 1981; Sneva et al. 1982); Pinatubo (Mercado et al. 1996)
Animal Health	Tooth abrasion leading to trouble grazing and premature aging. Eye irritation	Hudson (Wilson et al. 2011b): Puyehue-Cordón Caulle (Flueck, 2013; Wilson et al. 2012b); Paricutin (Rees & Angeles, 1970)	Low risk of fluorosis but unlikely at these thicknesses.	Cronin et al. 2003

B) Moderate - thick ashfalls (10-500 mm)

	Physical Impacts	Examples and References	Chemical Impacts	Examples and References
Soil	Tephra thick enough to form a barrier between soil and the atmosphere. Preventing soil, water and gas exchange.	Lanzarote (Diaz et al. 2005); Mt St Helens (Cook et al. 1981); Hudson (Wilson et al. 2011b); Puyehue-Cordón Caulle (Wilson et al. 2012b); Ruapehu (Cronin et al. 1998; Johnston et al. 2000); Fuego and El Chichón (Varekamp et al. 1984; Veneklaas, 1990); Others (Ayris & Delmelle, 2012; Smith et al., 2010)	As for thin ashfalls (Table 4.1a). Larger quantities of soluble elements may be available, but may need to be cultivated into soil to have positive effect.	Mt. St Helens (Dahlgren et al. 1999; Sneva et al. 1982); Kasatochi Island (Wang et al. 2010); Popocatepétl (Armienta et al. 2011) Others (Ayris & Delmelle, 2012; Ugolini & Dahlgren, 2002; Zheng, 2010)
Vegetation	As for thin ashfalls (Table 4.1a) Complete burial of the plant structure causing plant death. Overloading of plant causing breakages.	Merapi (Wilson et al. 2007); Mt. St Helens (Antos & Zobel, 1985; Cook et al. 1981; Dale et al. 2005; Seymour et al. 1983; Sneva et al. 1982); Hudson (Wilson et al. 2011a) ; Puyehue-Cordón Caulle (Wilson et al. 2012b)	As for thin ashfalls (Table 4.1a) Leachable elements may provide immediate stimuli to plant growth.	Merapi (Wilson et al. 2007); Mt. St Helens (Cook et al. 1981; Sneva et al. 1982); Pinatubo (Mercado et al. 1996) Soil (Kabata-Pendias, 2001; McLaren & Cameron, 1996; Shoji et al. 1993); Aerosols (Camuffo & Enzi, 1995; Decker & Christiansen, 1984; Frognerkockum et al. 2006; Nelson & Sewake, 2008; Phelan et al. 1982;Smith & Staskawicz, 1977)
Animal Health	As for thin ashfalls (Table 4.1a) Rumen blockages leading to starvation and/or internal injuries. Feed and water sources be smothered. Can also cause exposed feed to become unpalatable causing malnutrition.	Hudson (Wilson et al. 2011b): Puyehue-Cordón Caulle (Flueck, 2013; Wilson et al. 2012b); Paricutin (Rees & Angeles, 1970)	Tephra with moderate to high levels of available fluorine may cause acute or chronic fluorosis in grazing animals. Risk higher for pregnant animals or animals in poor condition. Polioencephalomalacia in cattle & sheep due to excess sulphur ingestion. Symptoms include brain damage and muscle spasms.	Hekla (Thorarinsson & Sigvaldason, 1971; Óskarsson, 1980); Ruapehu (Cronin et al. 1998; Cronin et al. 1997; Cronin et al. 2003; Johnston et al. 2000); Longquimay (Araya et al. 1990); Laki (Gestsdóttir et al. 2006); Popocatepétl (Armienta et al. 2011)

C) Very thick ashfall (>500 mm)

	Physical Impacts	Examples and References	Chemical Impacts	Examples and References
Soil	Fertile soil horizon completely buried and cut off from normal carbon, nitrogen and oxygen cycles. Water infiltration prevented.	Lanzarote (Diaz et al. 2005); Mt St Helens (Cook et al. 1981); Hudson (Wilson et al. 2011b); Puyehue-Cordón Caulle (Wilson et al. 2012); Ruapehu (Cronin et al. 1998; Johnston et al. 2000); Fuego and El Chichón (Varekamp et al. 1984; Veneklaas, 1990); Others (Ayris & Delmelle, 2012; Smith et al., 2010)	Loss of soil fertility as normal soil cycles cease.	Mt. St Helens (Dahlgren et al. 1999; Sneva et al. 1982); Kasatochi Island (Wang et al. 2010); Popocatepétl (Armienta et al. 2011) Others (Ayris & Delmelle, 2012; Ugolini & Dahlgren, 2002; Zheng, 2010)
			Ash deposits typically have low organic content and cation exchange capacity which limits their fertility.	Ayris & Delmelle, 2012; Shoji et al. 1993
Vegetation	Large amount of breakages due to tephra loading. Large clasts within the thick tephra fall strip and abrade vegetation.	Merapi (Wilson et al. 2007); Mt. St Helens (Antos & Zobel, 1985; Cook et al. 1981; Dale et al. 2005; Seymour et al. 1983; Sneva et al. 1982); Hudson (Wilson et al. 2011) ; Puyehue-Cordón Caulle (Wilson et al. 2012)	As for moderate ashfalls (Table 4.1b)	Merapi (Wilson et al. 2007); Mt. St Helens (Cook et al. 1981; Sneva et al. 1982); Pinatubo (Mercado et al. 1996)
	Pasture completely smothered requiring resowing. Seedings and younger crops and plants covered. Horticultural crops fail due to burial, breakages and abrasion.	Hudson (Wilson et al. 2011b)	Could cause damage to root apex due to acidity and aluminium complexes	Smith et al. 2010; Zheng, 2010
Animal Health	As for moderate ashfalls (Table 4.1b)	Hekla (Thorarinsson & Sigvaldason, 1971; Óskarsson, 1980); Longquimay (Araya et al. 1990); Laki (Gestsdóttir et al. 2006)	As for moderate ashfalls (Table 4.1b)	Hekla (Thorarinsson & Sigvaldason, 1971; Óskarsson, 1980); Laki (Gestsdóttir et al. 2006)

Table 4.2: Table of definitions used.

Term	Definition	Reference
Risk	The probability of negative consequences caused by an event.	UNISDR 2009
Risk assessment	A methodology used to predict the probability of an event's characteristics and the consequences, using a probabilistic hazard model and vulnerability assessment information.	UNISDR 2009
Impact	The effect a hazardous event has on an exposed system. Defined as a function of the hazard, and the vulnerability and exposure of a system (I = H V E).	Jenkins et al. 2014b
Pre-event impact assessment	Prediction of the consequences of an event using hazard scenarios (deterministic approach), vulnerability information and exposure inventories, that does not have probabilities attached to it.	Jenkins et al. 2014b
Post-event impact assessment	Assessment of the consequences of an event, and the hazard characteristics and vulnerabilities of exposed assets that influenced these consequences.	Jenkins et al. 2014b
Hazard	A phenomenon or event that poses a danger to life, property, economy, or social systems.	UNISDR 2009
Hazard intensity metrics (HIM)	The characteristics and properties of a hazard that can be measured and related to impacts.	Wilson et al. 2014
Exposure	People, property and systems that are within hazard zones and subject to impacts.	UNISDR 2009
Exposed assets (EA)	Asset types within the hazard zone.	UNISDR 2009
Vulnerability	How susceptible to damage the affected systems are.	UNISDR 2009
Vulnerability characteristics (VC)	The characteristics of a community, system, or assets that make it susceptible to the damaging effects of a hazard.	UNISDR 2009
Vulnerability Assessment	Methodology used to identify and/or quantify the vulnerability characteristics of an exposed system.	UNISDR 2009
Probabilistic hazard model		Bonadonna 2006
Deterministic hazard model	Scenario – based approach, where it is assumed that the hazard intensity is known.	Bonadonna 2006

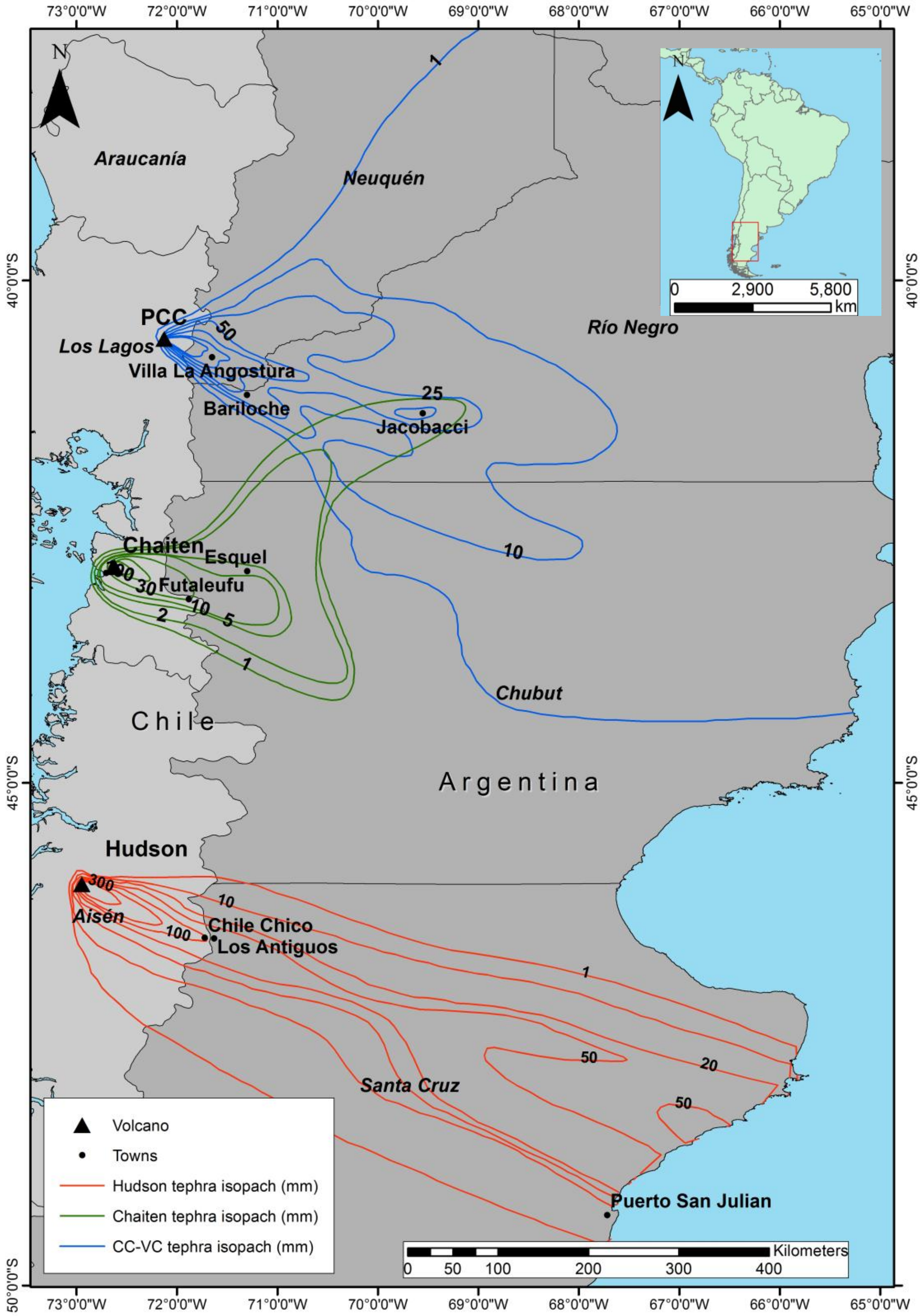


Figure 4.1: Map of showing the locations of the three study volcanoes and ashfall thicknesses across Chile and Argentina.

In this study we present and discuss post-event agricultural impact assessment data from three recent eruptions in Patagonia (Hudson, 1991; Chaitén, 2008; and Cordón Caulle, 2011). Impacts varied considerably with respect to both the depth of tephra fall, and with vulnerability characteristics (VC) such as farm size, farm type, and access to resources such as machinery and irrigation. This enabled us to evaluate how both the hazard intensity measures (HIM) and the VC interacted to generate the impacts observed. These large magnitude, explosive, silicic eruptions each deposited tephra over >75,000 km^2 in the Patagonian region of South America, including large areas of productive agricultural land (Fig. 4.1; Table 4.3) (Buteler et al. 2011; Martin et al. 2009; Wilson et al. 2011a). Each eruption caused substantial impacts to agriculture in each tephra fall zone. However, impacts varied considerably depending on the load of tephra received (kg/m^2), whether tephra was remobilised by aeolian or fluvial processes, the characteristics of exposed farms, time of year, local climate conditions, and the role and resources of supporting agencies. Developing an understanding how these factors influence impact or damage will improve risk assessments. This was investigated by relating indices of tephra hazard intensity and measures of vulnerability for exposed farms to impact observations. This paper presents a brief review of previous tephra impact and risk assessments for agriculture (Section 4.3), followed by the presentation of impact, hazard and vulnerability information across the three volcanic disasters and the emergency management strategies employed (Section 4.5). This information is used to inform a system of classifying impacts into a performance-based damage state scale (Section 4.6). The influence of tephra fall and exposed asset vulnerability characteristics on agricultural impacts, and how these will influence response and long-term recovery is discussed. Finally, considerations for future post-event tephra impact data collection for agriculture are discussed.

Table 4.3: Study site information (Smithsonian 2011).

	Hudson	**Chaiten**	**CC-VC**
Location	45.9°S, 72.97°W	42.83°S, 72.65°W	40.59°S, 72.12°W
Elevation (m)	1905	1122	2236
Volcano Type	Stratovolcano	Caldera	Stratovolcano/ fissure
Start Date	8-Aug-91	2-May-08	4-Jun-11
End Date	27-Oct-91	31-May-11	21-Apr-12
Volcanic Explosivity Index (VEI)	4 - 5	4	3
Magmatic Composition	Dacitic	Rhyolitic	Dacitic-Rhyolitic
Max. Plume Height (km)	18	15	13
Tephra fallout area (km2)	100 000	100 000	75 000
Year of last prior eruption (VEI)	1971 (3)	1642 (4)	1990 (1)
Previous eruptions	12 holocene eruptions. The largest was caldera forming 6 700 years BP.	Major caldera forming eruption 9400 years BP. Last prior eruption in 1640 (VEI 4).	Eruption in 1960 (VEI 3) deposited tephra over a similar area to the 2011 event.
Time of visit	Jan-Feb 2008	Jan-Feb 2009 and Mar 2012	Feb-Mar 2012
Time between eruption and field work	16 years, 5 months	9 months and 3 years, 10 months	9 months

4.3 Impact Assessments

4.3.1 Overview of impact assessments for natural hazard events

Impact and risk assessments both aim to quantify and predict the consequences of a hazard event, by relating hazard, exposure, and vulnerability characteristics (Smith, 2013) (see Fig. 1.3). The distinction is that impact assessments do not have probabilities attached to the different outcomes that could occur. Both types of assessments can be undertaken both before and after a hazardous event, and use scenario or probabilistic approaches (definitions in Table 4.2). Vulnerability assessments account for how the specific characteristics of a system influence impacts that will occur under different hazard intensities (Fuchs et al. 2012). For a full review of impact and risk assessments see Section 1.3.

4.4 Methods

Data for this study was primarily collected during impact assessment study visits in areas exposed to tephra fall after the three eruptions (summarised in Table 4.3). Agricultural areas were visited along a transect of the tephra fall zones approximately parallel to the main tephra fall out axis where possible. Participant-led, semi-structured interviews were undertaken and comprised of two main types: 1) technical interviews with agricultural agency and emergency management specialists, where general, non-social impacts were discussed; and 2) general interviews with farmers and farm managers about their experience in managing the tephra fall, where care was taken to ensure psychosocial impact discussions are avoided. Interviews were conducted in Spanish through a trusted interpretor with previous experience in both interpretation of research interviews and in the Patagonian setting. The translator was briefed on participant privacy and the need to avoid social and psychological lines of questioning. He formally agreed to abide by the ethical guidelines stated in the HEC application. Participants were required to complete and review a consent form available in Spanish. Interview methodology was reviewed and approved by the University of Canterbury (Christchurch, New Zealand) Human Ethics Committee prior to each trip. Interviewing was undertaken at varying times after the initial event (Table 4.3). These timings were chosen in order to allow time for the impacts to fully manifest (in the case of Chaitén and CC-VC) or to assess long-term recovery (Hudson). The methods used are described in Wilson et al. 2011 (for Hudson), and Wilson et al. 2012b (for CC-VC). The same methods were applied after the Chaitén eruption.

Interview data was compiled into tables and common themes identified. Interviews were undertaken using the rural question guidelines described in Table 2.3. The relationship between animal deaths and production losses, and the observed impacts was investigated to assess the farm impacts that occurred in order to cause significant production losses. All expert judgement and observations referred to in the study are based on field interviews with affected farmers, investigations made during field work for this study, and findings recorded during interviews with agricultural agency staff, emergency management personnel, and other affected stakeholders. In order to quantify this observational impact data, damage states were developed using performance-based indicators. This involved assessing production changes and the different mitigation strategies farms employed after the tephra fall (i.e., reliance of supplementary feed/aid), and then ascertaining what was the corresponding level of damage sustained for each of these groups of different production change scenarios. This meant that primarily qualitative data collected through interviews could be placed in a more quantitative framework, allowing for more accurate comparisons to be drawn. A limitation of this approach is the potential for incorrect and/or bias reporting of production losses by interviewed farmers. This could be due to genuine error and issues with recalling exact information, or farmers potentially offering misleading information. Incorrect information on the impacts to farm production could be provided due to a range of reasons, including trying to ensure that sufficient financial and practical aid is received. It is presumed that this effect is minimised by the interview team being from another country and having no formal connections with government or aid agencies. To support this assumption, trends in production losses appeared broadly consistent (see section 4.6), and correlated well with overall regional impacts reported by municipal managers. Despite uncertainties associated with relying on interview data, given the callenges of collecting such data it provides one of the few practical means of quantitavely assessing the impacts on production from tephra fall.

Data collected during interviews was also collated in order to assess the relationships between HIM, VC, and agriculture. Production change or animal deaths were compared to various hazard and vulnerability data that was collected in interviews in order to identify trends. This was undertaken to try and identify causal mechanisms for loss, which can then be used as a tool to both predict losses from future events, particularly with VC which can be assessed pre-eruption, and predict ongoing losses over the weeks and months after the initial tephra fall and impact assessment.

4.5 Agricultural setting and impact observations

In order to fully assess the VC of affected farms the regional setting and environment needs to be well understood, as aspects such as climate, soil type and ecosystems could potentially influence the impacts received. The study area covered a transect running from the temperate Andean environment of Chile in the east to the semi-arid Argentine steppe. Precipitation levels in the region vary widely, with the annual rainfall on the western coast of Chile exceeding 2,000 mm, with the opposite coast of Argentina recieving <200 mm per year. This difference is caused by the rain shadow effect, where a predominant westerly flow of air hits the Andes and causes a hyper-humid environment to form. Conversely on the downslope side only dry air arrives forming a semi-arid environment. This environmental difference also influences the soil types seen across the impacted areas. The dominant soil types in the study area are illustrated using the Food and Agriculture Organisation classification scheme (Fig. 4.2).

The soils in the study area generally become less fertile towards the east (from fertile andisols and cambisols in the temperate zone, to yermisols in the semi-arid region), which in conjunction with less precipitation, restricts the type and intensity of farming that can occur (Salazar et al. 1982).

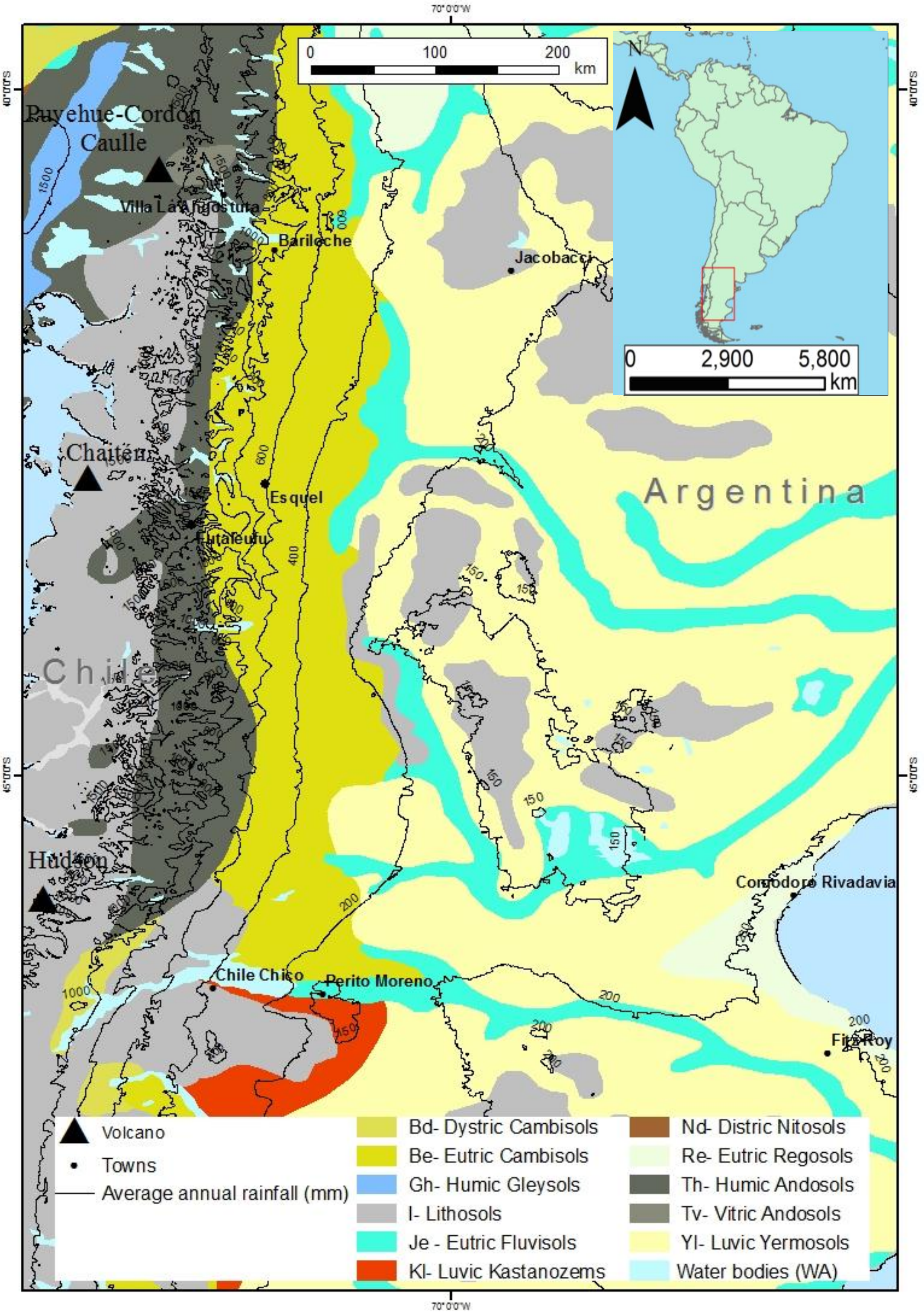
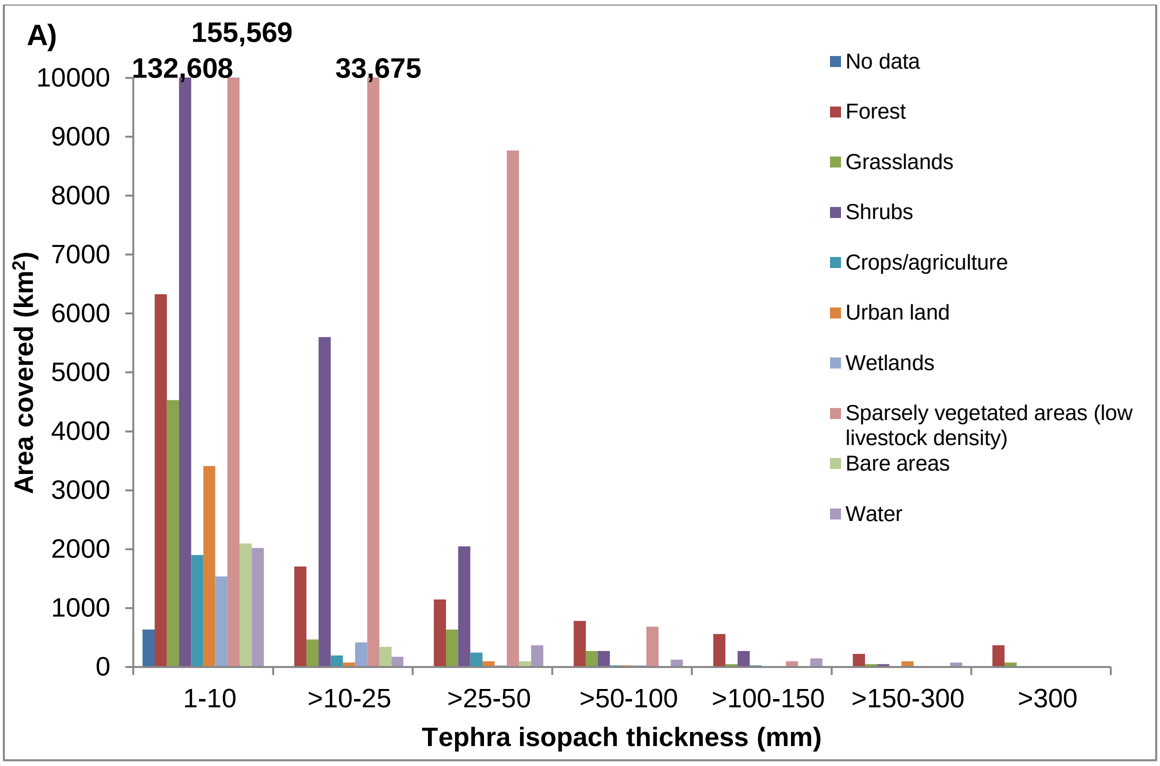


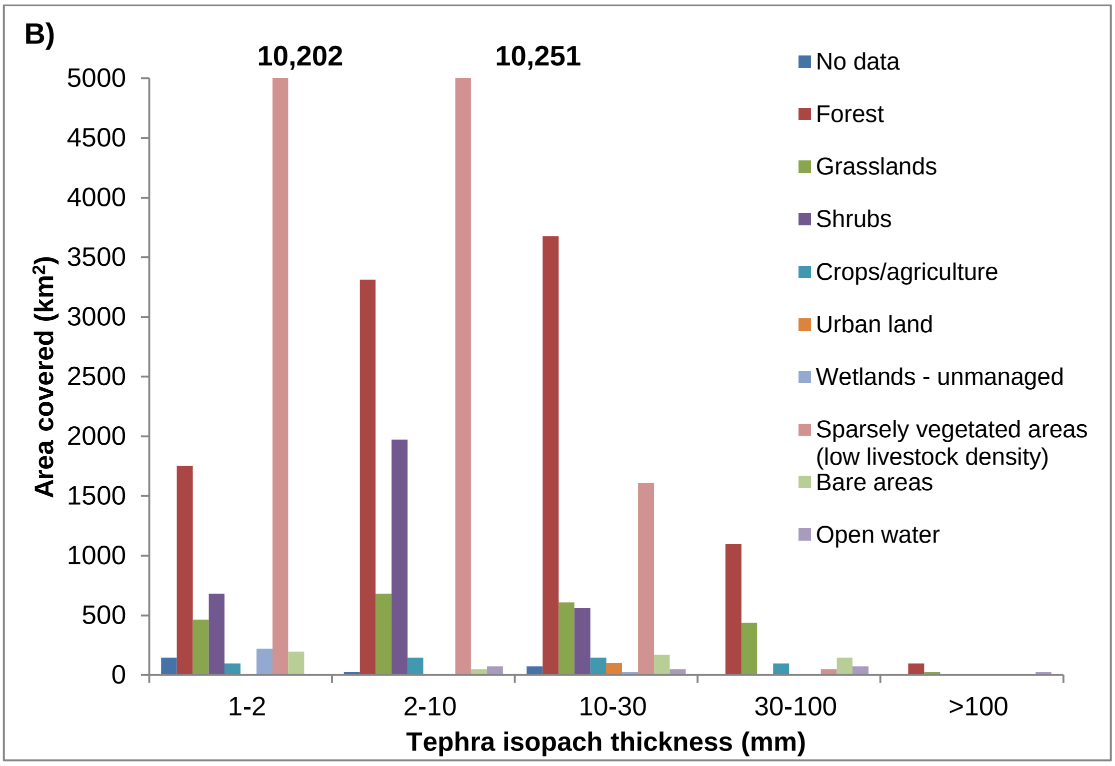
Figure 4.2: Map of the study area showing the different soil types and average annual rainfall across the depositional areas.

Areas in the temperate Andean zone have the capacity for high intensity farming, horticultural activities and cattle farming, whereas farms in the semi-arid steppe are more suited to relatively low intensity, sheep and goat farming where irrigation is not available (i.e., usually stocking rates of less than 1.5 animals/Ha) (Aruani & Sánchez, 2003). This creates two distinct zones of farming; the temperate zone (including the Nahuel Huapi National Park) and the semi-arid region (including Jaccobaci and the Comallo Valley).

Tephra fall affected a variety of land use types across a wide area (Fig. 4.3; Appendix B.1). At tephra thicknesses of >100 mm the majority of land affected is classified as 'Forest – with agricultural activities' (i.e., the Nahuel Huapi National Park agricultural area), with a considerable amount of 'urban area' (20%) also receiving 150-300 mm. At less than 100 mm the majority of tephra covered land was either 'shrubs – low livestock density' or 'sparsely vegetated areas – with low livestock density,' which represents the semi-arid, steppe farming region (Fig. 4.3; Appendix B.1; FAO, 2008).

The agricultural impact data presented was collected during interviews and field visits after the three tephra fall events and is summarised in Table 4.4.





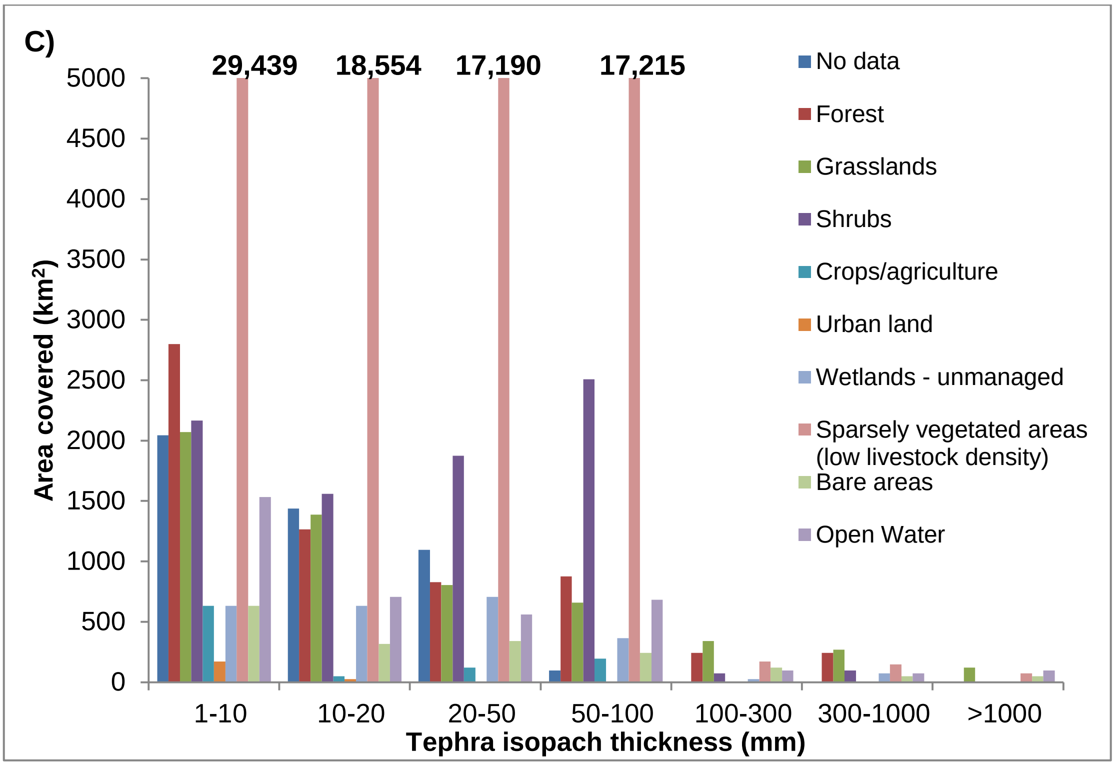


Figure 4.3: Area of land use types (FAO 2008) covered by tephra isopachs after each eruption for A) Hudson; B) Chaiten; and C) CC-VC. See Appendix B.3, B.4, and B.5 for raw data.

Table 4.4: Summary of the agricultural impacts across the three eruptions.

Event	Locality	Climate Zone	Species	Tephra thick-nesses (mm)	Wind remobilisa-tion (months-years)	Starva-tion	Abrasion		Immobilisa-tion of sheep due to tephra in fleeces	Livestock autopsy findings	Primary cause of livestock deaths	Vegetation issues	Produc-tion losses >50%
							Eye	Tooth					
Hudson^ 1991	Ibanez Valley	Temperate	Sheep, cattle	1500		✓		✓		Tephra blockages in rumen and gastrointestinal tracts	Immobilisation due to tephra fall, gastrointestinal blockages, starvation	Complete burial	✓
	Puerto Ibanez	Temperate	Sheep, cattle	250		✓		✓	✓	Asphyxiation due to intestinal blockage pressing on lungs	Immobilisation due to tephra fall, gastrointestinal blockages, starvation	Burial, breakages	✓
	Chile Chico	Temperate	Sheep, tomatoes, cherries, potatoes	100	✓	✓	✓	✓	✓	Tephra blocakges in gastrointestinal tracts	Gastrointestinal blockages, eye irritation, tooth abrasion	Wind abrasion, vegetation shearing	
	Cerro Castillo	Transitional	Sheep, tomatoes, cherries, potatoes	100	✓	✓		✓		Tephra blocakges in gastrointestinal tracts	Gastrointestinal blockages, eye irritation, tooth abrasion	Wind abrasion, vegetation shearing	
	Los Antiguos	Semi-arid	Sheep, tomatoes, cherries, potatoes	80	✓	✓	✓	✓	✓	Asphixiation due to intestinal blockage pressing on lungs	Gastrointestinal blockages, eye irritation, tooth abrasion	Wind abrasion, vegetation shearing	
	Perito Moreno	Semi-arid	Sheep	40	✓	✓	✓	✓			Gastrointestinal blockages, eye irritation, tooth abrasion	Wind abrasion, vegetation shearing	✓
	Tres Cerros	Semi-arid	Sheep	40	✓	✓		✓			Gastrointestinal blockages, eye irritation	Wind abrasion	✓

Event	**Locality**	**Climate Zone**	**Species**	**Tephra thick-nesses (mm)**	**Wind remobilisa-tion (months-years)**	**Starva-tion**	**Abraision**		**Immobilisa-tion of sheep due to tephra in fleeces**	**Livestock autopsy findings**	**Primary cause of livestock deaths**	**Vegetation issues**	**Produc-tion losses >50%**
							Eye	**Tooth**					
Chaiten 2008	Chaiten	Temperate	Cattle, sheep	350		✓		✓		Hard lumps of tephra completely blocking rumen	Starvation	Burial, breakages	✓
	Futaleufu	Temperate	Cattle, sheep	150		✓		✓		Hard lumps of tephra completely blocking rumen	Starvation	Burial, breakages	✓
	Esquel	Semi-arid	Sheep	5	✓	✓	✓	✓			Tooth abrasion, gastrointestinal blockages	Wind abrasion, vegetation shearing	
	Pilcaniyeu	Semi-arid	Sheep, goats	1	✓	✓		✓			Tooth abrasion, loss of condition	Wind abrasion, vegetation shearing	
CC-VC 2011	Nahuel Huapi National Park	Temperate	Cattle, deer, horses	350		✓		✓			Starvation, gastrointestinal blockages	Burial, breakages	
	Jacobacci/ Comallo	Semi-arid	Sheep, goats	50	✓	✓	✓	✓		Hard lumps of tephra completely blocking rumen	Tooth abrasion, loss of condition	Wind abrasion, vegetation shearing	✓

*Farming takes place within the national park where farmers lease a portion of the national park, however boundaries are not strictly adhered to
^Summary from Wilson et al. 2011

4.5.1 1991 Hudson eruption

The 1991 Hudson eruption primarily deposited tephra across the Aísen province of Chile and the Santa Cruz province of Argentina (Fig. 4.1). Tephra was deposited over 100,000 km^2, with thicknesses of over 1000 mm recorded in proximal areas (Table 4.3). Farming in the area is dominantly pastoral farming of cattle in the west and sheep on the eastern steppe, with horticulture concentrated in the valleys around Chile Chico and Cerro Castillo (Table 4.4). A full summary of the 30 farms interviewed and information collected is presented in Appendix B.2.

4.5.1.1 Pastoral impacts

Overall, an estimated 1 million animals died due to the tephra fall preventing normal grazing (Wilson et al. 2011a). This was due primarily to starvation and gastrointestinal blockages caused by tephra-contaminated feed. Tephra contamination either buried or made feed unpalatable for livestock and animal condition quickly declined.

The major cause of agricultural loss in areas which experienced <150 mm of tephra fall was extensive, prolonged wind remobilisation of tephra deposits. Issues with feed contamination and vegetation burial and damage were exacerbated in areas where wind remobilisation of tephra deposits meant that the vegetation was being semi-continuously covered with tephra, even many years after the initial eruption (Wilson et al. 2011b). Effects on livestock and vegetation due to wind remobilisation of tephra deposits were similar to those experienced with initial tephra falls, however the impacts occurred over much longer timeframes (Wilson et al. 2011a). At the time interviews were undertaken (over 16 years after the initial eruption) areas such as Puerto Ibanez (Chile) were still experiencing active wind remobilisation of tephra deposits, despite some effort to stabilise deposits and protect vegetation (re-vegetation, irrigation, wind breaks). This led to farm abandonments both immediately after the tephra fall and in the months afterwards as conditions persisted. Tephra stabilisation methods were based on experience with wind remobilisation after the 1980 Mt St Helens eruption, where cultivation or tilling tephra into the soil, revegetation of deposits, and tephra removal and capping were all employed (Collins & Dunne, 1986; Fowler & Lopushinsky, 1986).

In addition to these methods farmers also found that employing windbreaks (either shelter belts of trees, or plastic sheet fencing) also prevented the redeposition of tephra on crops and pasture. Farms that immediately attempted cultivation or deposit stabilisation were more able to withstand the wind remobilisation of tephra deposits over the months and years after the eruption (Wilson et al. 2011b).

The timing of the eruption occurred at the end of the winter before spring pasture growth could replenish pasture and improve waning animal condition. Pasture covered in a thin layer of tephra preventing growth was also an issue, even when thicknesses were as low as 1-2 mm. Additionally, some farmers also reported tephra cementing and forming a barrier between the soil and the environment, preventing the infiltration of water into the soil and pasture.

The hazard of fluorosis occurring in livestock due to tephra ingestion and contamination of feed and water supplies was a major concern for farmers after the eruption, especially with the high mortality rates. Tephra leachates can sometimes contain levels of fluoride that are toxic to livestock (Witham et al. 2005), such as after the 1970 Hekla eruption where thousands of sheep died due to acute fluorosis (Thorarinsson & Sigvaldason, 1971). The potential of the Hudson tephra to cause fluorosis was specifically considered, and excluded as a loss mechanism because of the relatively low F concentrations in the tephra (Rubin et al. 1994).

4.5.1.2 Horticultural impacts

Horticulture in the affected area typically experienced the loss of between one and three harvests, due to tephra fall and compounded by the continued wind remobilisation of tephra deposits. This caused abrasion and acid damage to flowers and leaves. Fortunately the tephra fall occurred at a time of year that was more favourable for horticulture than for pastoral farming, as flowering had not yet occurred (Wilson et al. 2009). However, this relief was short lived as wind remobilisation of tephra deposits in the Puerto Ibáñez, Chile Chico and Los Antiguos regions continued for many years after the eruption, damaging flowers and fruit. Many horticulture farmers resorted to the use of greenhouses or shelter belts for six years after the eruption (Wilson et al. 2011b).

4.5.2 2008 Chaitén eruption

Tephra from the 2008 Chaitén eruption was deposited across the temperate cattle farming in the Los Lagos province of Chile, and the semi-arid, sheep and goat farming of the Chubut and Río Negro provinces of Argentina. Interviews with 13 farmers, as well as agricultural agencies, and municipal production managers were undertaken across this region (Appendix B.3).

4.5.2.1 Pastoral impacts

Pasture in the Chaitén and Futaleufú areas was buried by up to 350 mm tephra leaving it inaccessible to livestock. This led to animals becoming malnourished and without evacuations or substantial supplementary feed succumbing to starvation. Due to dry conditions prior to the eruption pasture was already not in optimal condition leading to further losses.

Tephra thicknesses in the proximal region and ongoing wind remobilisation of the tephra deposit across the steppe meant that maintaining access to uncontaminated pasture was the biggest issue for preserving animal health. In the temperate, Andean region (Chaitén and Futaleufú), following the tephra deposition a period of heavy snow and rainfall hit the proximal region. This became an issue when in some areas the wet snow froze cementing the tephra fall, further increasing reliance on supplementary feed for animals. Despite wetter conditions aiding tephra incorporation, thicknesses of over 200 mm meant that there was still a shortage of available grazing land, which meant that many farmers in the area had to evacuate or sell livestock. As has been seen after previous events, such as 1999 Tungurahua (Leonard et al. 2005), 1991 Pinatubo (Mercado et al. 1996), and 1943-56 Paricutin eruption (Eggler, 1963), farmers forced to sell after tephra fall due to lack of available feed and declining animal condition received much lower prices for livestock than pre-eruption. This increased financial losses for individual farmers. In contrast, in the steppe region pasture quality continued to decline in the months after the eruption due to dry conditions and wind remobilisation of tephra deposits. As with the 1991 Hudson eruption, the climatic zone and wind remobilisation occurrence created a divide in impacts, where in the semi-arid steppe losses continued and recovery did not commence for many months after the eruption. Farmers reported some cases of vegetation shearing and areas of pasture being repeatedly re-buried by remobilised tephra deposits, particularly in the fertile lowland valleys where over-thickening occurred. Whilst wind remobilisation of tephra deposits was less severe in intensity, area, and duration than after Hudson, this still led to a high reliance on supplementary feed throughout the affected area and animal losses of up to 10% in an area (Pilcaniyeu) that only received 3-5 mm of initial tephra fall. Additionally, many farmers were concerned about the toxicity of the tephra fall when ingested by animals. Whilst tephra leachate analysis showed that the risk of chemical toxicity in livestock was very low (Durant et al. 2011), some farmers chose to sell livestock based on these fears.

4.5.2.2 Horticultural impacts

Horticultural and arable farming was observed in both the temperate and transitional zones, and in isolated areas in the steppe that had access to irrigation water. In the transitional zone where the temperate and semi-arid zones meet, tomato and other fruit and vegetable crops were grown under makeshift shelters or greenhouses. These farms had some losses due to vegetation burial and abrasion of leaves and fruit, but were able to recover relatively rapidly (within one harvest). This rapid recovery was due to greenhouses providing protection from ongoing wind remobilisation of tephra deposits and the accessibility of equipment for irrigation and tephra removal or cultivation for crops not in greenhouses.

Arable farms located in the temperate and transitional regions to the east of the volcano were also affected by tephra fall. The eruption occurred when crops were in juvenile stages before spring growth, leaving plants vulnerable to structural damage and burial. However, crop losses were few and farmers even reported increased yields of corn and wheat three years after the initial eruption. These increased yields were likely a consequence of the ‘mulching’ effect that the tephra provided, where it prevented the loss of soil moisture, and also possibly due to the addition of beneficial elements such as sulphur (Durant et al. 2011).

4.5.3 2011 Cordón Caulle (CC-VC) eruption

As with the two other Patagonia eruptions, interviews were undertaken with farmers, agricultural agencies, emergency management personnel, and agricultural agencies, across both the temperate zone predominantly in Chile and the semi-arid, Argentine steppe (Appendix B.4). Both environmental zones received tephra fall of greater than 50 mm in places and rely on agriculture as a major employer and contributor to the local economy.

4.5.3.1 Pastoral impacts

Studies undertaken in the Jacobacci area, by local agricultural agencies after the eruption identified that animals would have been unable to access pasture through thick tephra deposits (Siffredi & Ayesa, 2011). Estimates of the proportion of pasture becoming inaccessible due to tephra coverage ranged from 70-80% for very wet valleys, and up to 90-100% for drier mallines (Siffredi et al. 2011). This led to widespread cases of starvation, where farmers observed a progressive loss of animal condition resulting in death (Juan Escobar, Municipalidad de Ingeniero Jacobacci, 2012). In the Nahuel Huapi National Park, any pastoral species were buried by over 300 mm of tephra. This meant that animals relied on taller forage such as shrubs, or supplementary feed.

As with the previous two case studies there was a clear difference in impacts between the temperate, Andean zone and the semi-arid, Argentine steppe, driven by wind remobilisation occurrence. The steppe area experienced extensive tephra remobilisation; Jacobacci municipality staff estimated that livestock losses after the tephra fall were around 40-60% for a total regional herd of 225,000 sheep and 60,000 goats. The losses in Nahuel Huapi National Park were much lower despite the closer proximity to the volcano and greater tephra fall depth (Table 4.4), and were comparable to those experienced after a severe winter (around 21%) (Marcos Arretche, Proteccion Civil Municipalidad Villa la Angostura, 2012; Anselmi et al. 2012). The impact of the tephra fall was lessened, as many farmers understood that the tephra fall would compromise access to feed. Their response was to slaughter a small number of animals for their households, and to sell animals before their condition worsened.

As with the Hudson eruption farmers immediately were concerned with the potential for toxicity to livestock due to ingestion of tephra. In particular the possibility of acute fluoride toxicity was a concern and was the focus of leachate studies. Several studies have reported severe dental and skeletal fluorosis in wild deer populations in the depositional area of the eruption (Flueck and Smith-Flueck, 2013a; 2013b), and an increase in post-eruption rates of accumulation of fluoride (F) in bones of sheep on farms in the depositional area (Flueck, 2013). The levels of F accumulation in bones are considered by the author of the latter study to be highly likely to cause chronic fluorosis. However, levels were too low to accumulate in livestock rapidly enough to cause acute fluorosis (Chapter 3).

4.5.3.2 Horticultural impacts

The affected area contained very little horticulture due to the already challenging farming conditions in the steppe region and forest cover in the national park. A cabbage farm in the transitional region between semi-arid and temperate was reportedly abandoned due to the ongoing impacts from wind remobilisation of tephra. Horticulture, mainly consisting of fruit trees such as apple and pear, around the town of San Martin de los Andes was also affected (Graziano & Miserendino 2011). Fruit suffered abrasion and damage due to remobilised tephra fall and yields the season immediately after the tephra fall were low. However, the majority of farms recovered to near pre-eruption levels by the next harvest.

4.5.4 Overall themes

Overall, the major agricultural impacts from tephra fall and wind remobilisation of tephra deposits identified from the three events are summarised in Table 4.4. Contamination of clean feed and water supplies for livestock was the major agricultural impacts, and livestock evacuation, applying protection to crops to avoid burial and damage or contamination by the tephra fall were the most common response actions. Four factors that influence the type and severity of impacts were identified from common themes within the interviews (Table 4.5). These were: 1) tephra deposit thickness; 2) climatic region and amount of precipitation prior to and immediately after tephra fall; 3) time of year the tephra fall occurred during; and 4) farm ‘improvement’ assets (e.g., shelter, greenhouses, machinery for cultivation and irrigation).

Table 4.5: Table showing important HIM and VC identified through compiling factors that were identified as influencing agricultural impacts.

<table>
<tr><th rowspan="2">Scale</th><th colspan="2">HIM</th><th colspan="2">VC</th></tr>
<tr><th>Pastoral</th><th>Horticultural</th><th>Pastoral</th><th>Horticultural</th></tr>
<tr><td rowspan="3">Farm</td><td colspan="2">Thickness: All case studies reported greater agricultural losses in areas with greater thicknesses. Thickness and loading determined the amount of pasture available and the amount of damage to horticultural crops.
Grain size: Contributes to animal ingestion, adherance to crops, and also to its remobilisation potential</td><td colspan="2">Access to machinery: Farms able to remove or cultivate tephra recovered more rapidly
Seasonality: Tephra falls during breeding season (pastoral) or seeding and flowering (horticultural) are more likely to cause damage
Farmer awareness: Lower losses in areas where farmers were aware of tephra impacts and/or had experienced them before
Systems failures: Agricultural losses exacerbated if other interdependent services disrupted such as electricity, roading, communications</td></tr>
<tr><td colspan="2">Leachable chemistry of tephra: Acid burns on pasture and horticultural crops. Risk of fluorosis in livestock</td><td>Feed & water access: Clean feed and water, and access to supplementary feed determined animal mortality</td><td>Type of crop: Crops such as rice (i.e., paddy), potatoes, and onions (i.e., below ground) performed better after tephra fall than chilies, tomatoes and tobacco (i.e., above ground)</td></tr>
<tr><td colspan="2"></td><td>Animal shelter & feed storage: Protected animals from tephra ingestion, as long as tephra loading does not affect the structure
Pre-existing animal condition: Pregnant or malnourished animals more likely to die from starvation, dehydration, and fluorosis</td><td>Greenhouses: Use of greenhouses protected crop from tephra fall, as long as loading does not effect the structure</td></tr>
<tr><td>Regional</td><td colspan="2">Abrasiveness of tephra: Caused livestock tooth abrasion (pastoral), vegetation shearing and abrasion (horticultural), and damage to machinery
Remobilisation potential: The thickness, grain size, and location of tephra deposits will influence the spatial and temporal extent of any remobilisation.</td><td colspan="2">Climate: Low rainfall led to wind remobilisation, high rainfall caused lahars
Access to aid: The amount of aid (goods, services, and monetary assistance) available to each region.</td></tr>
</table>

4.5.4.1 Emergency management strategies

A further finding from the three volcanic disasters is the role of risk management strategies (pre- and post tephra fall) in reducing impacts. Whilst this may not be overly surprising, identifying the effectiveness of risk management strategies is an important contribution to global volcanic disaster risk management (K. Smith, 2013).

Effective emergency management that will lead to disaster risk reduction (DRR), can be separated into five main principles: pre-event mitigation and preparedness; warning/communication of event occurrence; the initial response; and post-event recovery (Haddow et al. 2013). These stages and the observed strategies across the three case studies are presented in Table 4.6 and discussed in detail in the following sub-sections.

Pre-event mitigation and preparedness

In order to effectively undertake DRR, long-term mitigation and preparedness strategies need to be put in place prior to an emergency event (Alexander, 2002) (Table 4.6). Few preparedness strategies had been developed on Chilean or Argentine farms prior to the Patagonian eruption events, due to the low risk perception associated with tephra fall risk. This perception was due to both the fact farmers believed that tephra fall events would be rare occurences, and that if they were to happen the impacts would be relatively benign in nature. However, one resilience building strategy was highly beneficial. During the 1990s and 2000s (prior to the Chaitén and CC-VC events) agricultural extension agencies supported the development of farm improvement assets to support diversification (particularly encouraged a mix of horticulture and pastoral agriculture within individual farms) and intensification (through the use of irrigation, fertilisation and cultivation methods) of agricultural production in the affected areas, which reportedly reduced production losses (particularly in the Chaitén and Futaleufú areas, see Appendix B.3) from tephra fall (Table 4.6). However, volcanic hazard-specific preparedness planning could be improved through planning exercises and review of emergency management strategies (Table 4.6).

Table 4.6: Management strategies across regions affected by the three eruptions, and changing damage states during recovery (^SAG Servicio Agricola y Ganadero; * INDAP - Instituto de Desarrollo Agropecuario, Chile; ** INTA - Instituto Nacional de Technologia Agropecuaria, Argentina, # only considered Argentina as impacts to Chilean agriculture minimal after CC-VC eruption).

	Manage -ment Stage	**Definition (Haddow et al. 2013; UNISDR 2009)**	**Optimal tephra risk management actions in agricultural setting**	**Refer- ences**	**Example where success- fully applied**		**Hudson 1991**		**Chaitén 2008**			**CC-VC 2011**	
							Chile	**Argentina**	**Chile**	**Argentina**		**Argentina#**	
							Aisen	**Santa Cruz**	**Los Lagos**	**Chubut**	**Rio Negro**	**Neuquen**	**Rio Negro**
Pre-event	**1. Pre-event mitiga- tion**	Prolonged actions taken during 'non-emergency' time to reduce risks to people and property from future hazards.	For agricultural systems this includes farming resiliant crops/animals, abandoning the most at-risk land, having shelter available, and covered water and feed supplies.	Neild 1998	2006 Merapi (Wilson et al. 2007).	**Actions**	Pre-event agricultural extension programmes enabled sharing of advice on methods to make farms more economically resilient (by diversifying products). These inadvertantly aided in tephra fall mitigation.	Marginal conditions pre-event meant that there was no focus on pre-event mitigation for tephra fall or any hazard other than drought and strong winds.	Pre-event agricultural extension programmes enabled sharing of advice on methods to make farms more economically resilient (by diversifying products). These inadvertantly aided in tephra fall mitigation.	Prior to the eruption there had been a focus on encouraging diversification of farming products and methods in the area. This was focussed mainly on drought resilience.		No specific mitigation measures in place due to the unique and dispersed nature of the farming. Farmers are used to some losses during winters and other natural events (such as storms) and accept this.	Prior to the eruption there had been a focus on encouraging diversification of farming products and methods in the area. This was focussed mainly on drought resilience.
						Issues	No tephra fall targeted mitigation programmes in place.	Drought the issue most commonly faced, however most farmers did not have the means to focus on mitigation. Use of shelter belts increased resilience.	No tephra fall targeted mitigation programmes in place.	Not all farmers wanted to diversify. Many did not have the financial means to do so. Limited awareness of volcanic hazards and risk.		No measures in place. Farmers usually do not live on grazing land and do not have frequent contact with livestock.	Not all farmers wanted to diversify. Many did not have the financial means to do so.

	Manage-ment Stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	Refer-ences	Example where success-fully applied		Hudson 1991 Chile Aisen	Hudson 1991 Argentina Santa Cruz	Chaitén 2008 Chile Los Lagos	Chaitén 2008 Argentina Chubut	Chaitén 2008 Argentina Rio Negro	CC-VC 2011 Argentina Neuquen	CC-VC 2011 Argentina Rio Negro
Pre-event	1. Pre-event mitiga-tion					Lessons	Targetted pre-event mitigation planning required. Farmers need to be made aware of available options and methods to minimise losses in future events.		Agricultural extension programmes, diversification efforts, and some awareness of Hudson contributed to pre-event mitigation. However, this was predominantly by chance rather than design.	Farmers with more diverse land use and access to new technologies were more resilient to the tephra fall.		Despite unique system, some pre-event mitigation and awareness strategies are needed in such a volcanically active setting.	Farmers with more diverse land use and access to new technologies were more resilient to the tephra fall.
Pre-event	2. Prepare-dness	Knowledge and capacity developed to respond to a event, an areas readiness to respond to an emergency event.	Preparedness utilises the assessment of the risk of tephra fall and the vulnerabilities of the exposed farms (identified pre-event). Planning for an event can then be undertaken including organisation of equipment, supplies and personnel. Preparedness plans need to be exercised.	Haddow et al. 2013; Alexander 2002	Ruape-hu 1995 (Johns-ton et al. 2000); Kelud 2014 (Blake et al. 2015).	Actions	Some planning in place by agricultural agencies, but not widely understood by farmers.		SAG^ preparedness plans in place. Equipment and organisation of personnel and resources in place for most areas.	Some emergency preparedness plans in place by INTA** (not volcano specific). Some feed supplies stockpiled in case of drought or severe winters.		Farming agencies had varying levels of knowledge about the Hudson and Chaiten events and their impacts on agriculture.	
						Issues	No preparedness initiatives on a farm scale.		Some issues with ensuring that plans were up to date and well understood.	Farming agencies had varying levels of knowledge about the Hudson event and its impact on agriculture.		Some preparedness plans in place by INTA**. Some feed supplies stockpiled in case of drought or severe winters.	
						Lessons	Clear planning, organisation of equipment, personnel training, and evaluation of preparedness strategies is needed for future events.		Continued refinement and evaluation of preparedness plans needed.	Clear planning, organisation of equipment, personnel training, and evaluation of preparedness strategies is needed for future events.		Clear planning, organisation of equipment, personnel training, and evaluation of preparedness strategies is needed for future events.	

	Manage-ment Stage	**Definition (Haddow et al. 2013; UNISDR 2009)**	**Optimal tephra risk management actions in agricultural setting**	**Refer-ences**	**Example where success-fully applied**		**Hudson 1991 Chile Aisen**	**Hudson 1991 Chile Los Lagos**	**Chaitén 2008 Chile Los Lagos**	**Chaitén 2008 Argentina Chubut**	**Chaitén 2008 Argentina Rio Negro**	**CC-VC 2011 Argentina Neuquen**	**CC-VC 2011 Argentina Rio Negro**
During event	**3. Communi-cation/ Warnings**	Strategies in place that provide warnings, notifica-tions and reports of the evolving situation to the commun-ity.	Clear, widely disseminated ashfall forecasts that include predictions on spatial distribution and hazard intensities. These need to reach both governmental and municipal level authorities and agricultural agencies. Warnings and forecasts then need to be disseminated to community rural groups and individual farms. Regular updates on the situation are also ideal.	Leonard et al. 2008	Mt. St. Helens (Cook 1981)	**Actions**	Increased seismic activity was noticed and interpreted as a pre-cursor to eruptive activity by many farmers who had experienced the 1971 eruption. Official warning and evacuations were given a day prior to the eruption.	Some warning received at a municipal level, but the majority of farmers in the region were not fully aware.	Warnings were received during the initial phase of the eruption, however the focus of these was on ensuring no risk to human life.	No official warning reached the majority of farmers. Municipal authorities were aware of the increased volcanic activity.		No official warning reached the majority of farmers. Municipal authorities were aware of the increased volcanic activity.	No official warning reached farmers or agricultura l agencies. Limited awareness and understand ing by municipal authorities.
						Issues	Translation of volcanic information into warnings with appropriate advice was not fully undertaken.	No event specific planning was undertaken for agricultural systems.	Timing and focus of warnings was on protecting humans, therefore many farmers still did not have time to shelter or evacuate animals.	Agricultural agencies and individual farmers were unable to sufficiently prepare. No event specific evacuation or aid plans could be fully provided.		Agricultural agencies and individual farmers were unable to sufficiently prepare. The lack of warning meant that farmers were unable to even place animals in shelter or cover feed and water supplies before the tephra fall began.	
						Lessons	Warnings need to be either accompanied by or recommend another source of emergency management and mitigation advice.	Issues with information transfer from scientists to municipal authorities to agricultural agencies & farmers. Complicated by inter-country.	Warnings need to be either accompanied by or recommend another source of emergency management and mitigation advice.	Issues with information transfer from scientists to municipal authorities to agricultural agencies and farmers. Further complicated by inter-country issues.		Improvement in information transfer from scientists to municipal authorities and agricultural agencies needed. Dissemination of volcanic unrest data through to emergency and response planning vital to minimising impacts. Inter-country communication further complicated the information transfer.	

	Management Stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Hudson 1991 Chile Aisen	Hudson 1991 Chile Los Lagos	Chaitén 2008 Chile Los Lagos	Chaitén 2008 Argentina Chubut	Chaitén 2008 Argentina Rio Negro	CC-VC 2011 Argentina Neuquen	CC-VC 2011 Argentina Rio Negro
Post-event	**4. Response**	Actions undertaken to address the short-term impacts of an event. Usually focussed on saving lives, property, and other important assets.	Response actions for agricultural systems immediately after a tephra fall event include: livestock evacuation, financial aid, and the supply of supplimentary feed.	Whitman 2014	1991 Pinatubo (Newhall et al. 1997); 2010 Tungurahua (Sword-Daniels et al. 2011).	**Evacuations**	INDAP* co-ordinated evacuation of livestock (5000 cattle and 3000 sheep).	INDAP* co-ordinated evacuation of livestock (cattle prioritised); animal sales.	SAG^ co-ordinated evacuation of livestock (cattle prioritised).	No organised evaculations some animal sales by farmers who felt that they did not have access to enough uncontaminated feed for animals to survive.	No organised evacuations, few sales.	Evacuations aided by municipal subsidies	Some animals sold, facilitated by INTA**
							Lack of trucks, low visibility due to tephra fall, and in some areas snow. Authorities and individual farmers questioned the economic feasibility of evacuations. There was also a lack of feed in locations that livestock were moved to and livestock markets became overwhelmed with sales causing a price decrease.		The provision of trucks and safe routes was an issue. As the eruption presented a risk of loss of life in a main population centre (Chaiten township), this was the focus of efforts and resourses. Economic viability of livestock evacuations questioned.	-	-	Implementation of evacuations was usually done at a farm scale, which meant that only those with the financial means were able to evacuate livestock. Evacuation planning did not occur until after the eruption was in progress.	
							Better planning of transport systems (i.e., provision of trucks) and understanding of locations that livestock can be evacuated to is needed. This will prevent as many farmers feeling compelled to sell livestock, depressing sale prices.		Better planning of transport systems (i.e., provision of trucks)			The lack of warning meant that evacuations could not be undertaken initially due to unnavigatability of Lake Nahuel Huapi.	

	Manage-ment Stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk manage-ment actions in agriculture	Refer-ences	Example where success-fully applied		Hudson 1991 Chile Aisen	Hudson 1991 Chile Los Lagos	Chaitén 2008 Chile Los Lagos	Chaitén 2008 Argentina Chubut	Chaitén 2008 Argentina Rio Negro	CC-VC 2011 Argentina Neuquen	CC-VC 2011 Argentina Rio Negro
Post-event	**4. Response**			Whitman 2014	1991 Pinatubo (Newhall et al. 1997); 2010 Tungurahura (Sword-Daniels et al. 2011).	**Fina-ncial aid**	Credit provided to use for cultivation, animal values paid out in most affected areas.	Subsidy based on production change due to eruption, interest free loans for improvements, supplementary feed for first 8 weeks, grant to replace any animals lost	INDAP* co-ordinated 100% value of animal paid out, credit for repair work/cultivation (US$500 per hectare-farmer paid then reimbursed by SAG)	Interest free loans for improvements (cultivation and shelter mostly), grant to replace any animals lost	Supplement ary feed given were requested	Paid out value of each animal by INTA (dead or alive). Municipally organised feed shipped across lake for first few months	400g of feed per animal, short-term interest free loans given
							-	Marginal conditions pre-eruption meant that some farmers chose to abandon farms rather than accessing aid.	Evacuations and abandonments made benefits of aid difficult to understand.	Many farmers chose to sell animals, at relatively low prices before accessing aid.	Due to marginal conditions pre-eruption supplementa ry feed requirement s were higher than expected.	Numbers of animals were often unknown as farmers withheld numbers for taxation reasons.	As the feed rates were calculated per animal, they did not take into account those with increase dietry needs, such as preganat or lactating animals.
							Paying out full values of animals decreased the pressure on evacuations and animal sales.	Pre-exisitng farm conditions and relative vulnerabilities need to be taken into account when assigning aid.	Difficulties with rapid, large-scale livestock evacuations was realised, pay outs for each animal were an effective management tool.	Increased understanding of aid available and mitigation options would have been bemeficial.	Pre-existing farm conditions and relative vulnerabiliti es need to be taken into account when assigning aid.	As the infeasibility of livestock evacuations was quickly realised, pay outs for each animal were an effective management tool.	Feed supplies need to be calculated with increased farmer input. Interest free loans provided good incentive for some diversification or farming and improvement of assets. However, many farmers did not want to.

	Manage-ment Stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	Refer-ences		Hudson 1991		Chaitén 2008			CC-VC 2011	
						Chile	Chile	Chile	Argentina		Argentina	
						Aisen	Los Lagos	Los Lagos	Chubut	Rio Negro	Neuquen	Rio Negro
Post-event	**5. Recovery**	Reinstatement and improvement of assets and community resources after an event. Often includes efforts to reduce future risk (contributing to pre-event mitigation efforts).	Assistance (advice, financial aid, and practical support) which allows for farmers to employ the most appropriate of the main recovery strategies recommended for agriculture after a tephra fall event. These include (Wilson et al. 2011a): 1) Tephra removal; 2) Cultivation of tephra into soil; 3) Reseeding of pasture/crop; 4) Targetted fertilisation; 5) Rinsing/irrigating of vegetation	Neild 1998; Wilson et al. 2009	**Manage-ment Advice**	1. Workshops given by INDAP*, evacuate where possible initially, cultivation advice given	INTA** led workshops, cultivation and re-seeding advised	Farmers advised by SAG^ to preferably strip off tephra, or cultivate in with disk ploughs	Advised to cultivate in tephra to stabilise deposit, use of windbreaks and shelter for animals		Evacuate where possible, shelter animals and provide alternative water source to lake and streams	Cultivate tephra into soil, vegetate and stabilise tephra deposit, shelter animals and provide clean food and water
						2. Relatively poor participation at farmer workshops.	Some information was not specific to the semi-arid steppe environment and the low intensity style of farming.	-	Some farmers felt unable to follow the advice due to the lack of access to funds and resources and challenges with farming in an area that was marginal pre-event.		Dispersed farmer population meant that communication was difficult and visits/workshops challenging to arrange.	Many farmers felt that the advice was too late, and many options were constrained by finances and access to resources.
						3. Pre-event agricultural extension programmes needed so that relationships are established before an event. This will increase farmer participation in post-event mitigation strategy workshops.	Advice needs to take into account the pre-existing farm conditions and the range of farm types.	Successful pre-event agricultural extension programmes, meant that agencies had estabilished relationships with farmers. This aided in trust and transfer of advice after the tephra fall.	Advice needs to take into account the pre-existing farm conditions and the resources that farmers have at their disposal.		Agricultural agencies were not necessarily set up to operate within such as dispersed and unique farming system, such as the Nahuel Huapi National Park. An information transfer system is needed.	Strongly benefited from Hudson and Chaiten previously occuring and the recovery lessons and awareness gained from these. Successful pre-event agricultural extension programmes, meant that agencies had estabilished relationships with farmers.

Warnings

Prior to, or immediately after an eruption has occurred, a timely, widely disseminated warning, which contains accurate and applicable information is an important part of effective volcanic emergency management (De la Cruz-Reyna & Tilling, 2008). Interviews with farmers and agricultural agencies suggested farms proximal to the volcanoes (within ~20 km) were both well informed and managed by responding agencies, or evacuated due to the natural cues for all three eruptions. However, beyond these distances effective warnings were not received at local level or farm level for all three eruptions (Table 4.6). Farmers beyond 20 km from the volcano typically reported that their first knowledge that an eruption had occurred was hearing explosions, sight of a volcanic cloud or the occurrence of tephra fall. Farmers unilaterally noted that provision of some warning would allowing emergency actions to be taken, such as sheltering animals, securing homesteads, and securing water and feed supplies.

Response

For pastoral farmers, once tephra began to fall livestock welfare management became a top priority. Livestock evacuations were undertaken in all three eruptions, but were area and context-specific (Table 4.6). Evacuations were prioritised based on the value of individual animals (e.g., cattle are more valuable than sheep), and where agricultural agencies had access to transport this was fully subsidised. Implementation at farm scale was usually left to individual farmers. This meant that only those farmers who had the financial means to access transport and alternate grazing land outside the impacted zone were able to evacuate animals. However, after the Chaitén and CC-VC eruptions, Chilean officials recognised issues with the feasibility of widespread livestock evacuations and paid farmers compensation based on the value of the animal regardless of whether it survived (Table 4.6). There was no clear tephra thickness threshold that necessitated livestock evacuation, rather the state of impact on the farms and transportation availability was assessed by agricultural agency officers (through visits on a ad hoc basis), and determined the compensation amount. This often proved more effective than undertaking evacuations, as the lack of available grazing for animals meant they either had to be sold cheaply or expensive rentals paid for grazing land. However, in some cases farmers felt they were underpaid for their animals, particularly in areas where exact animal numbers were not well-recorded or “adjusted” for taxation purposes. Increasingly, there is recognition of the value of livestock as both an economic and psychosocial asset for affected farmers.

Recovery

After the initial emergency period, both pastoral and horticultural farmers requested advice on how best to recover from the negative effects of tephra deposition. For pastoral farms the main recommendation given by agricultural agencies to remediate pasture was to either remove the tephra or cultivate it into the soil. For horticultural farms, rinsing tephra off the crops and building greenhouses and shelterbelts in areas prone to wind remobilisation of tephra deposits was the main advice given (Table 4.6). Farmers followed this advice to varying degrees, primarily dictated by what resources they could access, both within their own farm operations and external resources provided by government or municipal assistance. The areas affected by the CC-VC eruption benefited from the Chaitén and Hudson events, as managers were more aware of the recovery options available, which often led to clearer advice being given. In the semi-arid, steppe region, the majority of farms across all three depositional zones did not have access to machinery for cultivation and soon realised that removal of tephra was not suitable in an area where the deposit was still being remobilised. Financial credit was given to farmers for cultivation and re-seeding (Table 4.6). In areas that received >300 mm of tephra fall cultivation or removal was not possible and farmers were forced to wait for more gradual incorporation of tephra into the soil. Cultivation of tephra into the upper soil horizon was consistently found to speed up recovery and aid with pasture reestablishment. Some farms in the temperate region, after the Chaitén and Hudson eruptions, even reported an increase in pasture growth after cultivation of tephra into the soil (at tephra thicknesses of 10-100 mm). This has been observed after previous events, such as 1980 Mt. St. Helens (Cook et al. 1981), where farms which cultivated reported more rapid recovery and decreased fertiliser requirements compared to those that left the tephra deposit on top of the soil. Greenhouses and shelterbelts were found to be the most effective at aiding horticultural recovery and building resilience to tephra remobilisation. These methods are the same as those employed permanently in areas that receive multiple tephra fall events per decade, such as agriculture around

Merapi (Indonesia), Kelud (Indonesia), and Tungurahura (Ecuador) volcanoes (Blake et al. 2015; Sword-Daniels et al. 2011; Wilson et al. 2007).

In some areas of the Argentine steppe after the Chaitén and CC-VC eruptions there was confusion around how best to access information and aid money, and in rare cases some hesitance to follow the prescribed advice. Interviews suggested that farmers who did not take full advantage of aid packages were those that also had low community connectedness (not part of rural community groups, lacked strong links with neighbours), had not previously participated in agricultural extension programmes, and little faith in governmental and municipal authorities. This affected their ability to cope with the tephra fall and likely hindered their recovery and exacerbated losses. A consistent theme amongst many of the interviewees was the perception that people in the neighbouring country or province were receiving more aid or had a more positive future. When examined this often proved incorrect, and was more prevalent in those who were unaware of all available municipal mitigation and recovery initiatives.

4.5.4.2 Lessons

Overall, there are many management lessons that can be identified from the three eruptions (Table 4.6). These include:

- Targeted pre-event planning, including the establishment of agricultural extension programmes, awareness campaigns, and diversification schemes.
- Better organisation of management personnel and equipment, and continued evaluation and refinement of any preparedness plans.
- Clear pathways for information transfer from scientists, stakeholders, and farmers.
- Guidelines to aid decision making around livestock evacuations. These need to include when evacuations will be activated, how they will be transported, and locations livestock can be moved to, as well as estimates on the number of livestock that can be feasibly relocated and the economic costs of doing so.
- Increased communication between agricultural agencies and farmers, providing specific advice on how best to aid recovery from tephra fall.

4.6 Analysis of impacts

The following section presents a set of damage states based on the interview and observational data collected after the three Patagonia events and information collected after previous post-EIA of agricultural areas affected by tephra fall (Section 4.5). Damage/production states were created to categorise the impacts that occurred at interviewed farms in order to convert the qualitative interview data into a scaling system, which will then be compared to different HIM (Section 4.6.2) and VC (Section 4.6.3).

4.6.1 Damage/production states

Damage/production states were developed by assessing the factors that influenced agricultural losses predominantly using interview data from the three case studies presented here, as well as previous impact assessment case-studies (Table 4.7). Damage states provide a measure of common states of damage caused by the natural hazard and exposed element (See Section 1.3 for further explanation). These factors included production base losses (e.g. livestock illness and death for pastoral; crop losses for horticultural), external assistance (e.g. supplementary feed, evacuations, cultivation, and/or mitigation assistance), and overall productivity losses. These factors were separated into a damage/production state scale based on theoretical steps in damage, impacts and production losses observed elsewhere (Table 1.1), and production losses associated with different impacts after the three Patagonian eruptions. Five main states of damage were identified using the factors described above, and associated production changes, which are presented in Table 4.7. Five damage/production states (DPS) were chosen in order to classify farms with no impacts (DPS0), farms with some impacts that could economically recover with minimal external assistance (DPS1), farms that needed varying levels of assistance (DPS2 and 3), to farms that could not longer operate at all (DPS4). The damage/production states were designed to be applied at a farm scale in order to address all damage and changes in the productivity of pastoral and horticultural farms.

Table 4.7: Proposed performance based damage states created to catalogue impacts at the various farm interview sites across the three eruptions.

Damage State	Description	Pastoral				Horticultural	
		Large farms (>500 ha)		Small farms (<500 ha)			
		Effects on production	***Damages***	**Effects on production**	***Damages***	**Effects on production**	***Damages***
0	**No disruption**	No production change	*No damage*	No production change	*No damage*	No production change	*No damage*
1	**Some disruption**	Minimal, absorbed within normal boundaries of fluctuating production (<25% production loss)	*>75% pasture available; Some grazing still available*	Supplementary feed required to maintain production (>15% production loss)	*<75% pasture available; Pasture available not enough to sustain livestock*	Slightly lower productivity but recoverable harvest	*<75% vegetation covered*
2	**Moderate disruption**	Some supplementary feed required, adverse health effects in exposed animals (~25-50% production loss)	*~50% pasture available; Pasture available not enough to sustain livestock*	Large amount of supplementary feed required (15-50% production loss)	*60-40% pasture available; Most animals unable to graze, animal deaths begin, open water sources contaminated*	<25% production loss	*Some plant breakage and damage to crops; possible acid burns and abrasion*
3	**High disruption**	Total reliance on supplementary feed, widespread animal sales and evacuations (>60% production loss)	*<25% pasture cover; Animals unable to graze due to tephra cover*	Entire season production lost, discontinuation of normal farm activities (e.g., mating, shearing, etc.) (>50% production loss)	*Animals unable to graze due to tephra cover, majority of animals dead, in poor condition, or sold, basic soil fertility indicators (N, P, K) negatively affected*	Rinsing/mitigation needed, ~50% production loss	*Most crops sustained some damage*
4	**Total loss of capabilities**	Widespread mitigation and rehabilitation needed in order for production to resume (>70% production loss)	*Very low likelihood of soil recovery in the next 12 months, >50% animal deaths*	No production possible for at least one year (>70% production loss)	*Total abandonment of farm - often permanent, vegetation dead*	>70% reduction in yield; >1 season to recover,	*All crops damaged in some way; damage to greenhouses*

The pastoral farm damage/production states are separated into two scales, as different farming practises occur on different sized farms which affect vulnerability to tephra impacts. Smaller farms are also less likely to be creating a substantial profit margin pre-event (compared to larger farms of the same type and intensity), which leaves them more vulnerable to production losses. Horticultural farms were not split into small and large farm groups as they were found to be more homogenous.

For pastoral farming, the end members of the scale represent no damage and maximum possible damage, where DPS0 is a farm that is completely unaffected by tephra fall (changes in production within expected ranges for a normal farm cycle), and DPS4 is a farm that suffers damage that is severe enough to completely halt production. The division of the intermediate states of damage (damage/production states 1-3) are predominantly based on productivity levels and the expected time and steps needed to recover to pre-event production. At DPS1 (some disruption) productivity losses are up to 25% for large farms and up to 15% for small farms. The majority of farms are assumed to recover to pre-event production levels within a year. At DPS2 (minor disruption) productivity losses are up to 50% and it is assumed they will take >1 year to fully recover. At DPS3 (high disruption) productivity losses are usually greater than 70% and large numbers of animal deaths, sales and evacuations occur and mitigation measures will occur before productivity returns to pre-eruption levels (Table 4.7).

Damage/production states for horticultural farming are less robust due to the smaller number of farm sites within this study (nine farms), but rely primarily on productivity changes following tephra fall. Horticultural farms within DPS0 will not suffer any production losses, DPS1 will sustain losses that can be recovered within a season, whereas DPS2, DPS3, DPS4 will sustain up to 20%, 50%, and 70% production losses respectively (Table 4.7). There was not a wide range of damage/production states presented in the horticultural farm sample, as most farms were located primarily within the same geographic zone (usually in the transitional zone between temperate and semi-arid zones, where rainfall is still greater than 250 mm/year, but not in the Andean region), therefore received similar thicknesses of tephra fall. This accounts for the more arbitrary scale based on production losses, rather than the theoretical and observational basis for the pastoral scale.

This scale was applied to the pastoral and horticultural farm sample visited across the three events and compared to percentage production changes (Fig. 4.4). Due to the retrospective nature of the study, damage/production states were applied using production change data, in addition to the observed impacts. However, if applied to future events the states could be assigned based solely on descriptors and give some indication as to the associated production losses that may occur.

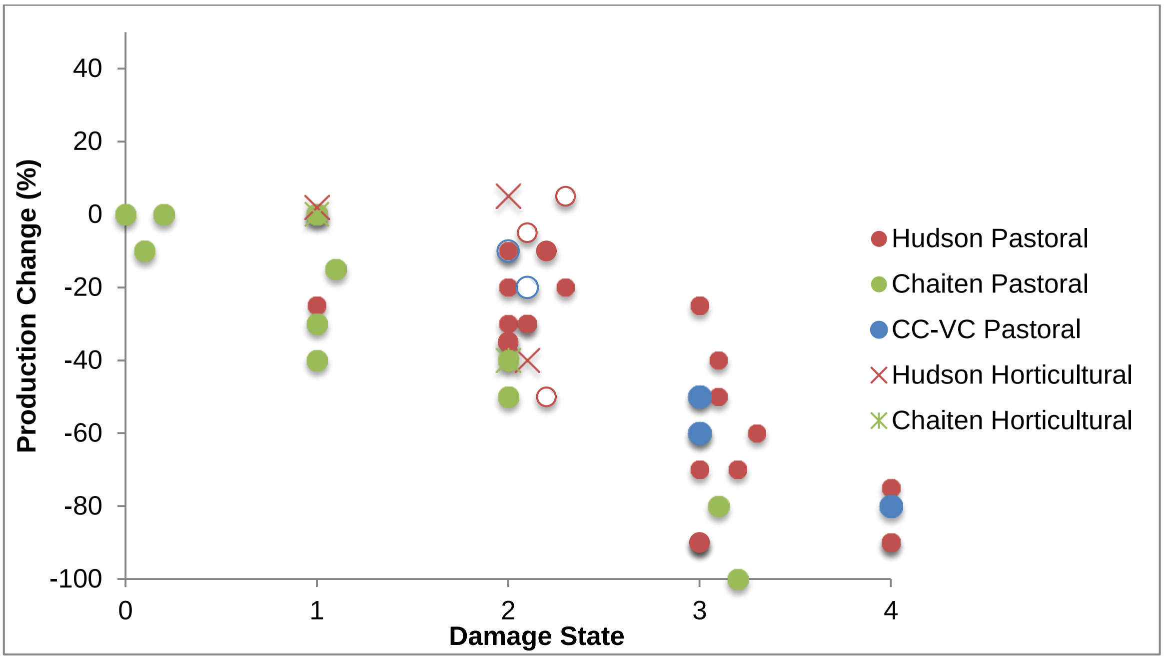


Figure 4.4: Damage state data for agricultural production change across the three eruptions.

4.6.2 Hazard intensity measures

As it is most commonly recorded (Jenkins et al. 2014b; Wilson & Kaye, 2007), tephra deposit thickness (mm) was used as the main HIM in this study. Therefore, the relationship between tephra thickness and the occurrence and severity of damage was investigated. Tephra thickness was an accurate indicator of animal deaths and production losses within each climate zone, particularly in the temperate zones (Table 4.8). However, prolonged (months to years) wind remobilisation of tephra was reported to greatly compound impacts at all farms across all three eruptions. When case-study farms are aggregated across the study areas and ranked in order of decreasing tephra thickness the exposed farms within the temperate zones for Hudson and Chaitén show a decrease in animal deaths and production loss (Table 4.8). This decrease in loss with decreasing thickness is not as evident for farms in semi-arid areas where tephra thickness still has an influence on impacts but the importance of wind remobilisation of tephra in compounding impacts becomes more evident.

However, when the data is not aggregated by region, tephra thickness alone was not a good predictor of animal deaths (Fig. 4.5) or production change (Fig. 4.6), with no clear relationship observed, especially at less than 200 mm thickness. This suggests that at these thicknesses there are likely other factors that determine losses (i.e., other HIM or VC). It is likely that these factors (especially VC) are more homogenous within regions accounting for the clearer trend in impacts with thickness on a regional scale (Table 4.8).
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Table 4.8: Average regional animal death (%) and production change (%) from aggradated interview data within the temperate and semi-arid climatic zones ranked by tephra thickness.

	Climate zone	Location	n	Max. tephra thickness (mm)	Mean tephra thickness (mm)	Min. tephra thickness (mm)	Max. animal deaths (%)	Mean animal deaths (%)	Min. animal deaths (%)	Max. production change (%)	Mean production change (%)	Min. production change (%)
Hudson	Temperate	Ibanez Valley	5	1000	600	100	100	70	38	-100	-75	-40
		Cerro Castillo	6	100	100	70	100	60	0	-80	-45	-20
		Puerto Ibanez	6	40	50	40	91	30	0	-80	-40	-15
	Semi-Arid	Chile Chico	5	100	100	100	50	30	0	-40	-10	0
		Los Antiguos	4	80	80	80	100	40	0	-25	-30	5
		Tres Cerros	1	NA	40	NA	NA	90	NA	NA	-90	NA
		Puerto San Julian	1	NA	5	NA	NA	NA	NA	NA	-80	NA
		Rio Gallegos	1	NA	1	NA	NA	20	NA	NA	-10	NA
Chaiten	Temperate	Chaiten	5	300	300	150	100	40	0	-100	-63	-15
		Futaleufu	3	150	150	150	0	0	0	-40	-25	-10
	Semi-Arid	Esquel	2	5	5	5	0	0	0	0	0	0
		Pilcaniyeu	3	5	5	5	10	5	4	-10	-10	0
CC-VC	Temperate	Nahuel Huapi	2	350	350	350	0	2	3	-20	-15	-10
	Semi-Arid	Jacobacci/Comallo	3	40	47	50	73	38	17	-80	-63	-50

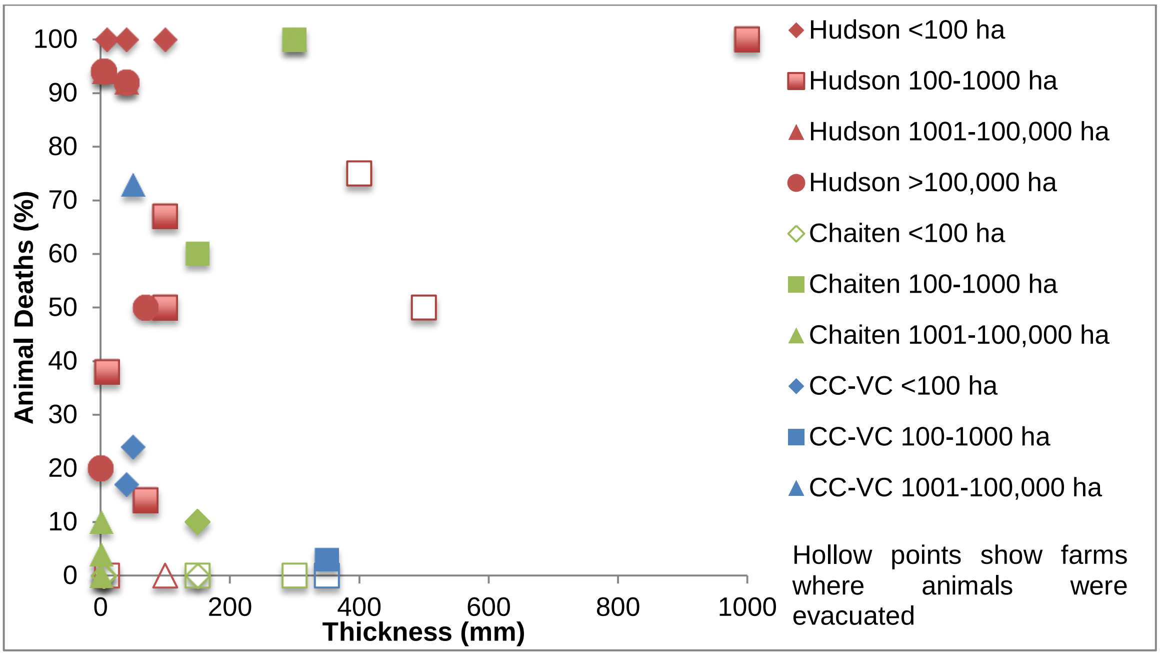

Figure 4.5: Animal loss percentage with ashfall thickness for various sized farms across the three eruptions.

Tephra thickness was also tested as a predictor of damage/production states, which better capture qualitative impacts, likely recovery times, as well as production changes. Damage/production states show some relationship with tephra thickness (Fig. 4.7). This is more pronounced when the data is separated into farms in the temperate and the semi-arid zones. This suggests that whilst thickness has some limitations when considering impacts across diverse regions, it does have some utility within climatically-similar regions (and in turn other VC, such as pre-existing animal and farm intensity differences). The relationship between tephra thickness and impacts is also more evident when areas of different tephra fall duration and remobilisation severity are separated (in the semi-arid area wind remobilisation of tephra deposits over months-years after the eruption intermittently made conditions similar to continuous tephra fall events). Average thicknesses associated with each damage/production state show that an increased damage/production state occurred at lower thicknesses in the semi-arid region. This is particularly evident when considering the higher states, where mean thicknesses at DPS3 and DPS4 in the semi-arid zone occurred at only 25 and 75 mm thickness, whereas in the temperate zone these states occurred with much higher thicknesses, at 225 and 535 mm respectively (Table 4.9 a).

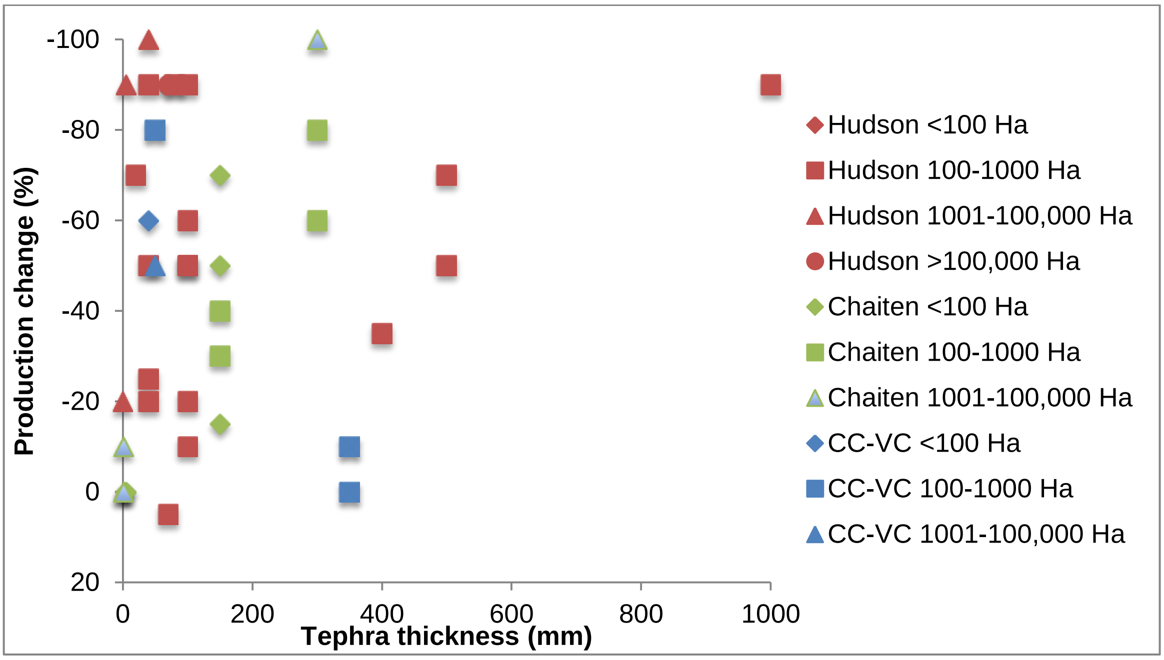

Figure 4.6: Farmer perception of productivity change after the three eruptions with tephra thickness.

Although the number of HIM included in the comparative analysis was limited, some conclusions can nonetheless be drawn and insights emerge. Tephra thickness remains the property most likely to indicate the damage/production state of the affected area (and therefore severity of impacts) during post-event assessment and when developing forecasting capacity with pre-EIA and risk assessments. Tephra thickness is an especially important predictive measure when considering impacts at a regional scale rather than on a farm-by-farm basis where an holistic understanding of individual farm operations and assets may not exist. Using tephra thickness to predict the damage/production state (a cruder measure of impacts) of the affected area appears to be more accurate than using specific loss information such as animal deaths or production losses. However, caution is needed when only using tephra thickness, because the clear differences between the temperate and semi-arid results demonstrate the importance of taking into account VC and other properties of the exposed systems.

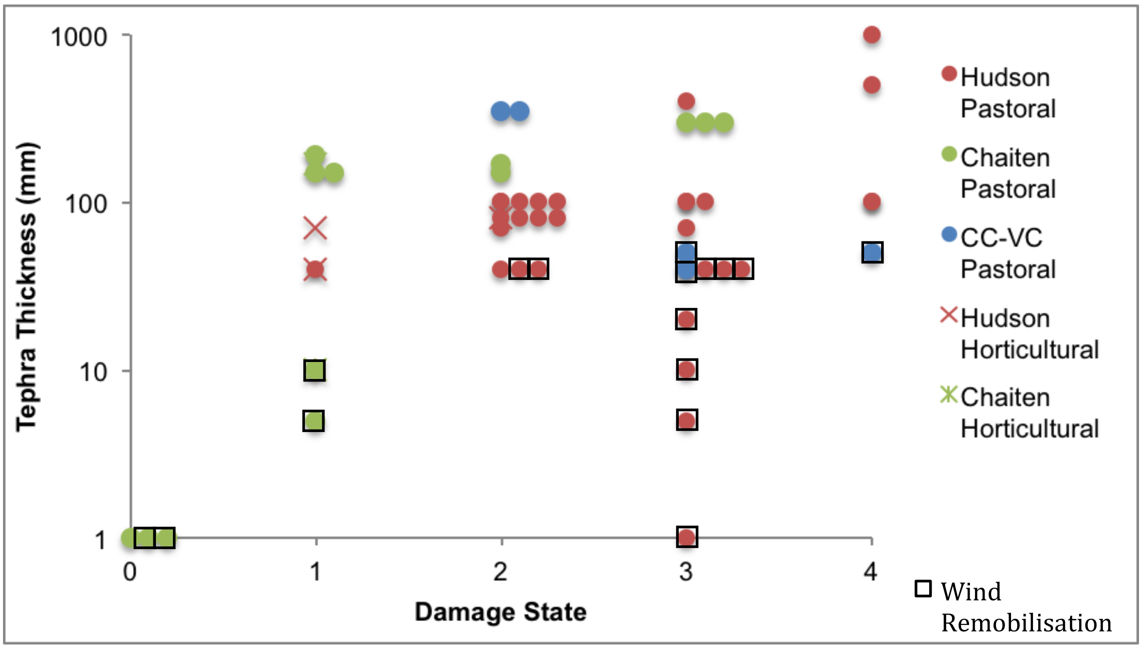

Figure 4.7: Damage state data for pastoral and horticultural agriculture across the three eruptions with initial recorded ashfall thicknesses.

Table 4.9: Mean tephra thicknesses (and standard deviations) associated with each damage state with various vulnerability characteristics (rounded to the nearest 5 mm).

	Damage State	n	DS0	DS1	DS2	DS3	DS4
A)	**Temperate**						
	Mean tephra thickness (mm)	28	-	130	130	225	535
	Standard deviation (mm)		-	60	100	130	400
	Semi-arid						
	Mean tephra thickness (mm)	21	1	10	40	25	75
	Standard deviation (mm)		0	5	0	20	35
B)	**Pastoral**						
	Mean tephra thickness (mm)	37	5	110	110	120	410
	Standard deviation (mm)		0	70	30	145	380
	Horticultural						
	Mean tephra thickness (mm)	8	-	40	150	-	-
	Standard deviation (mm)		-	-	40	-	-
	Mixed						
	Mean tephra thickness (mm)	4	-	-	150	300	-
	Standard deviation (mm)		-	-	35	-	-
C)	**Access to irrigation and cultivation machinery**						
	Mean tephra thickness (mm)	17	5	125	85	250	750
	Standard deviation (mm)	17	0	55	10	190	250
	No access to irrigation and cultivation machinery						
	Mean tephra thickness (mm)	32	-	5	160	70	180
	Standard deviation (mm)	32	-	5	110	90	190

Blank squares show where not enough data points with the applicable VC were observed within that DPS.

4.6.3 Vulnerability characteristics

In order to evaluate the influence that the VC of a farm has on impacts, the tephra thickness thresholds for each damage/production state were compared to farms with different vulnerability characteristics (Table 4.9). This allows the identification of the relative influence each VC has on farm vulnerability to tephra fall. The VC evaluated were:

1. the climatic zone the farm is located in (Table 4.9 a);
2. farm type (Table 4.9 b);
3. access to irrigation/cultivation machinery (Table 4.9 c).

The importance of seasonality (i.e., the season the tephra fall occurred in) was also assessed. However, the lack of variety in the data points (all three eruptions occurring in late autumn or winter) did not allow for comparison of damage/production state tephra thickness thresholds. These VC were assessed, as they all have appeared to influence impacts after previous events (Table 4.5), and consistently recorded during interviews, and can be easily recorded in future post-EIA.

4.6.3.1 Climatic zone

Observed agricultural impacts were also strongly influenced by climatic zone. Farms in the temperate, Andean zone did not experience the same widespread, long-term wind remobilisation of tephra deposits as those on the semi-arid, Argentine steppe. Severe impacts to vegetation and animal health were often seen at comparatively thin tephra fall depths (DPS3 and 4 were reached at 25 and 75 mm respectively, compared to 225 and 535 mm respectively in the temperate zones; Table 4.9 a). Additionally, lower standard deviations for the thickness thresholds in the semi-arid region (compared to the temperate area) show the strong control that the semi-arid environment will have on impacts. Large standard deviations in the temperate zone likely imply that other VC will also strongly influence the tephra thicknesses at which impacts occur (Table 4.9 a). Wind remobilisation of tephra deposits prolonged impacts to vegetation and livestock by reburying pasture and crops, and continuously contaminating feed and open water supplies. For example average overall farm production losses after the CC-VC tephra fall for interviewed farms in Jacobacci (semi-arid) were ~60% despite receiving less than 60 mm of tephra; in contrast farming within the Nahuel Huapi National Park (temperate) received more than 300 mm of tephra but only experienced overall farm production losses of ~15% (Table 4.6). This pattern was observed across all of the three Patagonian events with semi-arid areas (≤250-500 mm/year rainfall), where production losses and animal deaths occurred even in areas where less than 3-5 mm of tephra was deposited (Tables 4.6, 4.7 & 4.8).

The climate (in particular precipitation levels) is also important due to the interconnectedness of the other VC of a farm with the climatic setting. As farming within the semi-arid steppe was marginal pre-eruption, low-intensity farming took place and farms had little access to 'improvement' assets (see Section 4.6.3.3.). Another VC influenced by climate was the pre-existing condition of animals and crops, which determined their resilience to the effects of tephra fall. Animals in the steppe region were often slightly malnourished compared to those in the temperate zone. Climate is also a valuable predictive tool as areas of low rainfall where wind remobilisation of tephra deposits occurred (usually <250 mm/year) can be identified pre-eruption. These factors left farms in the semi-arid region vulnerable to negative impacts due to tephra fall, resulting in relatively low tephra thicknesses causing high damage/production states compared to the temperate region (Table 4.9 a).

4.6.3.2 Farm type

The type of farming is also important, as different types of farming showed greater or lesser resilience to the tephra fall. Horticultural farmers, particularly in the in Chile Chico and Los Antiguos regions following the Hudson tephra fall, usually experienced a much lower decrease in production than their pastoral counterparts, despite being exposed to comparable tephra fall thicknesses and subsequent wind remobilised tephra. These horticultural farms had access to irrigation and cultivation equipment, which aided tephra stabilisation and incorporation into the soil. The coarser grainsize of the tephra compared to the soil in those locations also reduced soil water retention, increasing irrigation demand (Wilson et al. 2010). Pastoral farms by comparison did not cope well by relying on natural (i.e. non-assisted) pasture recovery, especially where wind remobilisation of tephra was prevalent. The most resilient were mixed-farms utilising both livestock and crop production. This diversity meant farmers could adapt to focus on the most productive sources of income. Whilst diversification of production was a key focus of local agricultural agencies, many areas (particularly the steppe) simply could not adapt due to lack of access to irrigation water supply.

Although the majority of farms assessed for this study were pastoral it appears that horticultural and mixed (pastoral, arable and/or horticultural) were more resilient to the tephra fall. This is demonstrated by the higher tephra thicknesses required to cause more severe damage/production states (Table 4.9b). This resilience is likely due to horticultural farms having access to ‘improvement’ assets such as cultivation, irrigation and fertilisation machinery. Additionally, some horticultural farming in the region was confined to greenhouses that protected the crop from tephra fall contamination.

4.6.3.3 Access to ‘improvement’ assets

Pastoral farms that had access to clean feed, clean water, and shelter for animals, and horticultural farms with greenhouses and irrigation systems, suffered fewer impacts than farms that did not have these ‘improvement’ assets. Farms with access to cultivation machinery to mix tephra into soil also recovered more rapidly and sustained lower overall production losses. These assets helped to mitigate impacts and particularly fostered a more rapid recovery. Typically, farms in the semi-arid region were less likely to have access to improvement assets prior to the tephra fall as they used a low-intensity, extensive farming model. However, some farms in the region did already have some shelter for animals and greenhouses for crops due to the challenging environmental conditions, which were advantageous. Pastoral farms that had shelters in the semi-arid region around Pilcaniyeu (after Chaitén) and Jacobacci (after CC-VC) experienced much lower losses than farms in the same region without shelter (~15-20% lower animal deaths). Similarly horticultural farms that used greenhouses in the Chile Chico region (1991 Hudson eruption) could continue production mostly uninterrupted despite 100-200 mm of tephra and severe wind remobilisation of tephra (Wilson et al. 2011a). Where greenhouses weren’t utilised in the temperate zone, cultivation machinery was used to stabilise the tephra deposit by incorporating it into soil or extensively irrigating to dampen and stabilise tephra deposits. These improvement assets and treatments were unaffordable or impractical to use in the large, extensive farms in semi-arid areas. This further exacerbated the divide between the climatic zones and their associated impacts.

The influence that the accessibility of machinery for cultivation/irrigation had on impacts is demonstrated by the damage/production state tephra thickness thresholds (Table 4.9c). Farms with no access to machinery reached DPS4 at a mean tephra thickness of only 180 mm, whereas those farms that were able to immediately begin irrigation and cultivation needed an average of 750 mm of tephra to reach DPS4. This trend was also observed for DPS1 and DPS3 (Table 4.9c). This demonstrates the importance of investment in ‘improvement’ assets as a pre-event mitigation strategy, because having access to irrigation/cultivation substantially decreased the vulnerability of the farm to damage.

4.6.3.4 Seasonality

The season and associated farm processes occurring during the time of the tephra fall were also influential in determining the impacts to a farm. In the Hudson tephra fall zone, cattle and sheep were in late-stage pregnancy, increasing their energy requirements and thus vulnerability to reduced feed availability. Farmers were also eagerly awaiting the spring growth period as feed-stocks were dwindling and animal condition poorer than during the summer months (Wilson et al. 2011a). A similar issue occurred in the CC-VC region where farmers were near the beginning of winter and grazing relief in the form of spring growth was still a few months away. This put pressure on feed supplies usually used to supplement animal grazing during the winter. The Chaitén eruption occurred earlier in the year (early May, at the end of Autumn) at a time when feed supplies were higher (Fig. 4.8). However, wool length amongst sheep was at its longest and shearing was about to commence. Tephra clogged fleeces, abraded shearing equipment, and reduced the number of animals shorn per hour. This led to a 25% decrease in the volume of saleable wool in some areas. Horticultural farms also had different levels of vulnerability to the tephra fall dependent on the type of crop and the time of year. After the Chaitén eruption, cherry and other fruit trees were dormant and so experienced few if any impacts compared to the severe impacts experienced by cherry farmers in Los Antigos and Chile Chico from tephra remobilisation during spring and summer periods when trees were blossoming and fruiting.

The three Patagonian events demonstrate the importance of recording VC information when predicting and minimising impacts to agriculture. This is evident especially when considering impacts over a smaller scale where thickness and other HIM could be very similar but the impacts between farms could differ due to specific VC. Due to the influence that VC has on impacts and relative damage/production states it is that these are captured in both pre- and post- EIA.

4.6.4 Recovery

The recovery of agricultural areas after a tephra fall was assessed to highlight which HIM and VC are slowing agricultural rehabilitation, and also to demonstrate which mitigation techniques accelerate the return to normal production levels. Recovery patterns were assessed by comparing damage/production states at the time of maximum losses (within 6 months after the eruption), with the damage/production states observed when interviews were conducted (197 months after the initial eruption for Hudson, 9 and 46 for Chaitén, and 9 months after for CC-VC) (Fig. 4.9). This showed that damage/production states in the semi-arid areas all remained elevated for much longer than those in the temperate zone. After over 16 years, farms in the temperate region (<200 km from the vent) affected by Hudson tephra falls have mostly returned to DPS1 in the region where tephra falls were greater than 400 mm, and zero in areas with smaller thicknesses. However, farms in the semi-arid area, which received much less tephra, have not returned to a DPS0 even after many years (Fig. 4.9 a). A similar trend was also observed after the Chaitén and CC-VC eruptions where damage/production state rebound did not occur as rapidly in the semi-arid zones (Fig. 4.9 b & c, area beginning >100 km from vent for Chaitén, >80 km for CC-VC).

The mitigation, aid, and advice given will also have a large influence on the recovery time. In order to compare aid given across the three eruptions, management actions were split into four categories (Fig 4.9). Level 0 meaning no aid or assistance, level I showing farms were given supplementary feed, advice, and/or interest free loans/tax breaks; level II for farms where a percentage of animal value was paid out, feed supplies were given, along with subsides and grants for recovery; level III was where total animal value was paid out, allowances for recovery were given on a per hectare basis, and subsidies and loans were widely available; level IV is where 100% of land and animal value was paid out. Areas in level IV were all within 100 km of the vent and had high damage/production states, usually due to the very thick tephra fall deposits received. Farms within this area showed a decrease in their damage/production states within 9 months (for Chaitén and CC-VC, Fig. 4.9 b & c) despite these thicknesses. In contrast, areas that received level I and II assistance did not always return to DPS0, despite having lower maximum damage/production states than farms in level IV (Fig. 4.9). This demonstrates the importance of practical aid solutions in agricultural recovery.

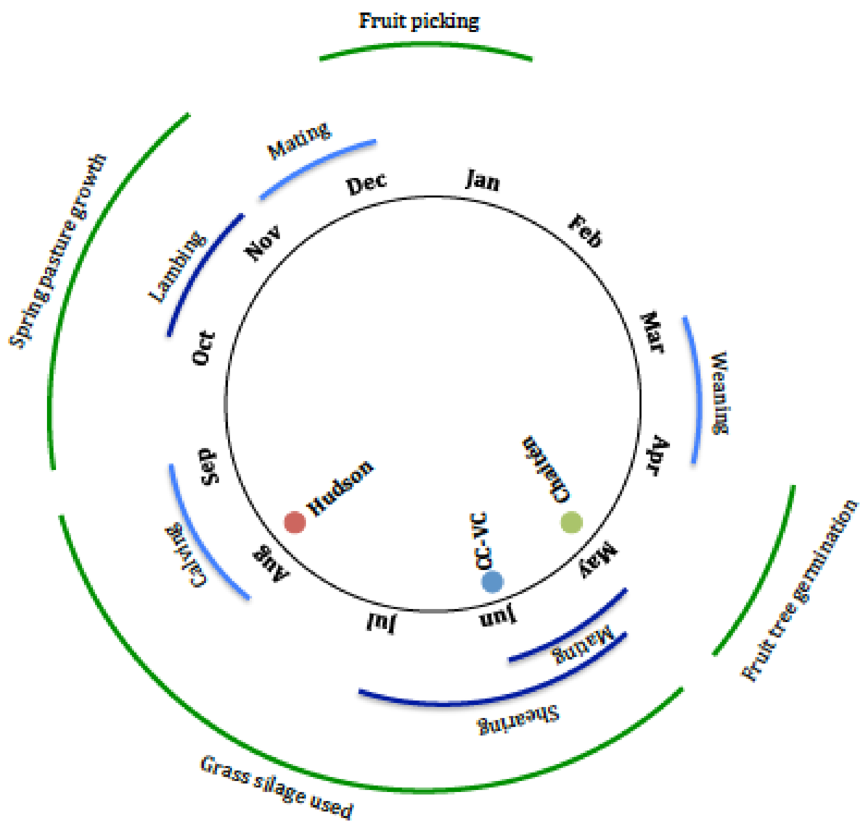

Figure 4.8: Seasonal occurrence of eruptions and corresponding farm activity. Centre points show tephra fall start dates, pale blue lines representing cattle, dark blue lines representing sheep, and green lines representing vegetation cycles.

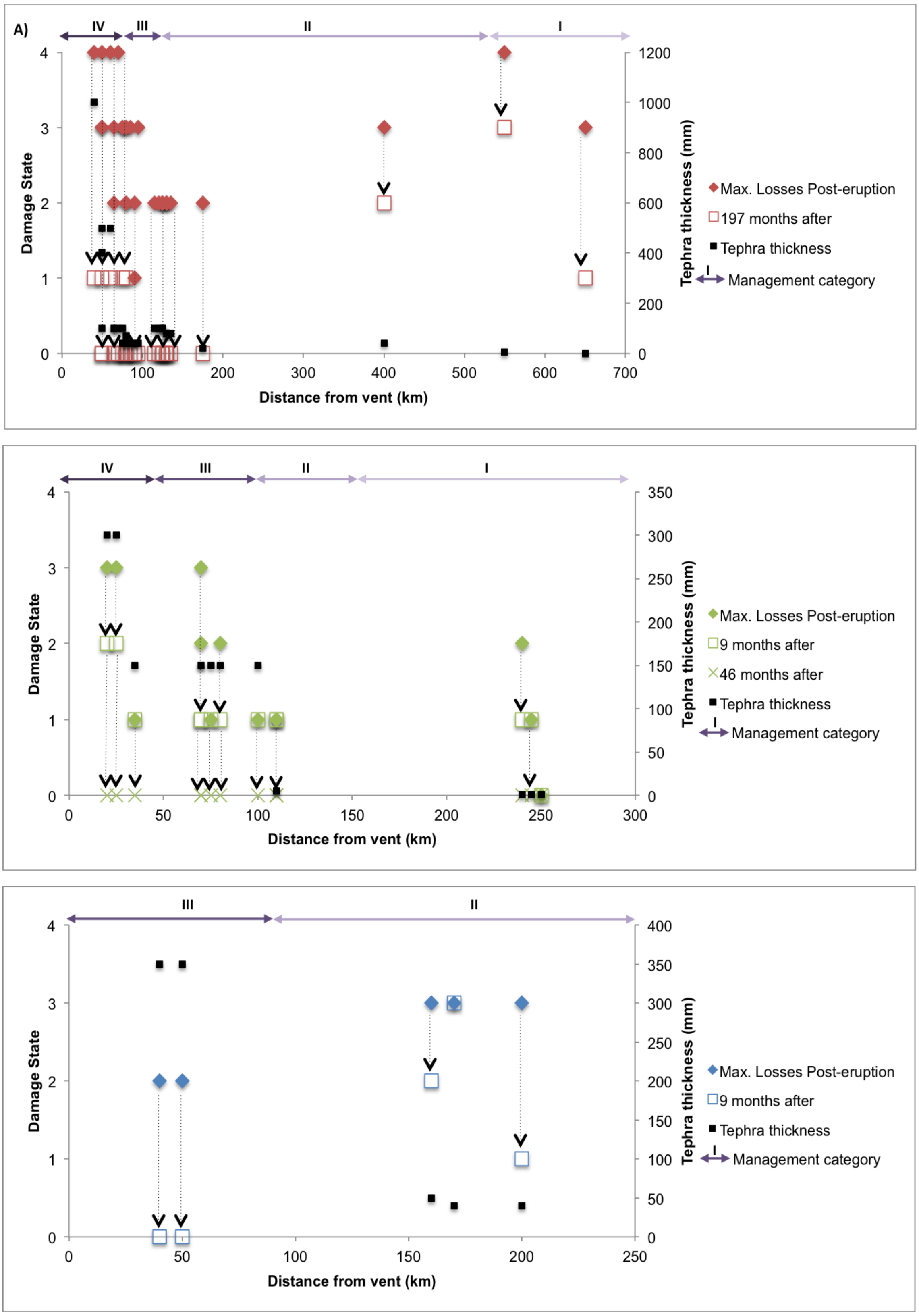

Figure 4.9: Agricultural recovery assessment using damage states recorded at time of maximum loss, and subsequent visits for A) Hudson, B) Chaiten, and C) CC-VC.

In order to increase understanding of agricultural recovery after tephra fall and allow for better identification of effective mitigative strategies, longitudinal studies need to be undertaken. Longitudinal study sites need to be selected to consider a range of farm types and intensities, as well as a broad cross-section of hazard intensities. They also need to be systematically assessed using robust methods over a period of months to years after the tephra fall event to understand the complete recovery process.

4.7 Lessons for future impact assessments

This study outlines the importance of not simply considering the hazard properties (HIM) when forecasting or assessing tephra fall impacts, but also integrating information on existing farm conditions and vulnerabilities (VC). This needs to be considered both pre-eruption when identifying areas of vulnerability and methods to increase resilience, but also post-eruption when assessing the occurrence and distribution of impacts in order to develop management plans. This holistic approach to risk assessment will ensure that risk models are more accurate and more widely applicable in the future.

Vulnerability characteristics of a farm can be identified pre-event. This means that high losses in areas of relative vulnerability can be planned for and management plans and farmer education can be put in place. Areas such as the Argentine steppe and other low rainfall (<250 mm/year) volcanic areas are likely to experience tephra remobilisation after an eruption. Awareness of tephra deposit stabilisation measures and plans to access machinery and materials to do this could minimise future losses and speed up recovery.

Whilst no single HIM or VC could accurately predict impacts for these three events, prolonged wind remobilisation of tephra deposits and the associated climatic conditions are a vital VC of the affected system. Initial tephra thickness proved an inaccurate predictor of loss that led to less aid being allocated in areas that then subsequently suffered greater losses than expected (i.e., semi-arid steppe region). Future emergency management and recovery planning needs to take this into account as it is likely that other tephra fall events will have impacts that can be better constrained with another HIM or VC in addition to tephra thickness.

4.8 Conclusions

The Hudson, Chaitén, and CC-VC eruptions provide an opportunity to study the different impacts, and controls on impacts, to agricultural systems in the Patagonian region. The area is unique in that three large silicic eruptions in the last 25 years have occurred within 600 km of each other, and all have tephra plumes and affected areas following along the same west-east environmental gradient. The following conclusions can be drawn from the three Patagonian events:

1. Agricultural impacts in the semi-arid, Argentine steppe, across the three events, were more severe than expected considering the relatively low initial tephra thicknesses received (<100 mm). This is because of the low intensity farming in challenging environmental conditions where there is not always access to 'improvement' assets. This leaves farms vulnerable to tephra fall impacts.
2. Agricultural damage/production states for tephra fall were developed using previous case studies; and interview data and production losses from the three Patagonian events. This allowed for impact data to be categorised into a standard framework and tephra thickness thresholds to be assigned for each state. These thresholds were more robust (i.e., had greater predictive power) when farms were separated into temperate and semi-arid regions, illustrating the importance of considering climate when predicting agricultural impacts.
3. Analysis of farm damage/production states with tephra thickness and influential VC led to the following conclusions:
    a. The complex interaction of HIM and VC of the exposed area will determine the impacts to agricultural systems after tephra fall.
    b. Both the HIM and VC of an area need to be understood and, where possible quantified, in order to provide accurate pre- and post- EIA.
    c. This study also identified that the most influential (and easily measurable) HIM when predicting agricultural impacts is tephra

thickness. However, tephra thickness alone is an insufficient predictor of impacts.

d. When considering the VC which determine impacts, climate (and the corresponding tephra remobilisation potential); farm type and size; and access to farm ‘improvement’ assets, were found to be important predictors of impacts. These VC could be identified pre-event to identify areas that may need more aid or targeted mitigation.
e. The proposed damage/production state scheme and tephra thickness thresholds could be applied to other events, during both pre- and post-EIA, to quantify and monitor impact information, which can inform management strategies.

4.9 Acknowledgements

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4.10 References

Alexander, D. (2002). Principles of emergency planning and management. New York: Oxford University Press.

Antos, J. A., & Zobel, D. B. (1985). Recovery of forest understories buried by tephra from Mt. St. Helens. Vegetatio, 64, 103–111.

Araya, O., Wittwer, F., Villa, A., & Ducom, C. (1990). Bovine fluorosis following volcanic activity in the southern Andes. Veterinary Record, 126(26), 641–642. Retrieved from http://www.cabdirect.org/abstracts/19902210133.html

Armienta, M. a., De la Cruz-Reyna, S., Cruz, O., Ceniceros, N., Aguayo, a., & Marin, M. (2011). Fluoride in ash leachates: environmental implications at Popocatépetl volcano, central Mexico. Natural Hazards and Earth System Science, 11(7), 1949–1956. http://doi.org/10.5194/nhess-11-1949-2011

Aruani, M. C., & Sánchez, E. E. (2003). Fracciones de micronutrientes en suelos del Alto Valle de Rio Negro, Argentina. Ciencia Del Suelo, 21(2), 78–81.

Ayris, P. M., & Delmelle, P. (2012). The immediate environmental effects of tephra emission. Bulletin of Volcanology, 74(9), 1905–1936. http://doi.org/10.1007/s00445-012-0654-5

Baker, J. (2014). Efficient analytical fragility function fitting using dynamic structural analysis. Earthquake Spectra, In press. Retrieved from http://earthquakespectra.org/doi/abs/10.1193/021113EQS025M

Blong, R. (2003). A new damage index. Natural Hazards, 30, 1–23. Retrieved from http://link.springer.com/article/10.1023/A:1025018822429

Blong, R. J. (1984). Volcanic hazards: A sourcebook on the effects of eruptions. Sydney: Academic Press.

Bonadonna, C. (2006). Probabilistic modelling of tephra dispersion Reference. In H. M. Mader, S. G. Coles, C. B. Connor, & L. J. Connor (Eds.), Probabilistic modelling of tephra dispersion (pp. 243–259). Geological Society, London.

Buteler, M., Stadler, T., López, G. P., Lassa, M. S., Liaudat, D. T., & Fernandez-arhex, D. A. V. (2011). Propiedades insecticidas de la ceniza del complejo volcánico Puyehue-Cordón Caulle y su posible impacto ambiental, 70, 149–156.

Camuffo, D., & Enzi, S. (1995). Impact of the clouds of volcanic aerosols in Italy during the last 7 centuries. Natural Hazards, (1970), 135–161. Retrieved from http://link.springer.com/article/10.1007/BF00634530

Collins, B. D., & Dunne, T. (1986). Erosion of tephra from the 1980 eruption of Mount St . Helens. GSA Bulletin, 97(7), 896–905.

Cook, R. J., Barron, J. C., Papendick, R. I., & Williams, G. J. (1981). Impact on agriculture of the Mount St. Helens eruptions. Science (New York, N.Y.), 211(4477), 16–22. http://doi.org/10.1126/science.211.4477.16

Cronin, S. J., Hedley, M. J., Neall, V. E., & Smith, R. G. (1998). Agronomic impact of tephra fallout from the 1995 and 1996 Ruapehu Volcano eruptions , New Zealand. Environmental Geology, 34(April), 21–30.

Cronin, S. J., Hedley, M. J., Smith, R. J., & Neall, V. E. (1997). Impact of Ruapehu ash fall on soil and pasture nutrient status 1 October 1995 eruptions. New Zealand Journal of Agricultural Research, 40(January), 383–395.

Cronin, S. J., Neall, V. E., Lecointre, J. A., Hedley, M. J., & Loganathan, P. (2003). Environmental hazards of Fluoride in volcanic ash : a case study from Ruapehu volcano, New Zealand. Journal of Volcanology and Geothermal Research, 121.

Dahlgren, R. A., Ugolini, F. C., & Casey, W. H. (1999). Field weathering rates of Mt. St . Helens tephra. Science, 63(5), 587–598.

Dale, V., Swanson, F., & Crisafulli, C. M. (2005). Ecological responses to the 1980 eruptions of Mt. St. Helens. Springer.

De la Cruz-Reyna, S., & Tilling, R. I. (2008). Scientific and public responses to the ongoing volcanic crisis at Popocatépetl Volcano, Mexico: Importance of an effective hazards-warning system. Journal of Volcanology and Geothermal Research, 170(1-2), 121–134. http://doi.org/10.1016/j.jvolgeores.2007.09.002

Decker, R., & Christiansen, R. (1984). Explosive eruptions of Kilauea Volcano, Hawaii. In Geophysics Study Committee (Ed.), Explosive volcanism: Inception, evolution and hazards (pp. 122–132). Washington D. C.: National Academy Press.

Diaz, F., Jimenez, C. C., & Tejedor, M. (2005). Influence of the thickness and grain size of tephra mulch on soil water evaporation. Agricultural Water Management, 74(1), 47–55. http://doi.org/10.1016/j.agwat.2004.10.011

Durant, A. J., Villarosa, G., Rose, W. I., Delmelle, P., Prata, A. J., & Viramonte, J. G. (2011). Long-range volcanic ash transport and fallout during the 2008 eruption of Chaitén volcano, Chile. Physics and Chemistry of the Earth, Parts A/B/C. http://doi.org/10.1016/j.pce.2011.09.004

Eggler, W. A. (1963). Life of Paricutin Volcano, Mexico, eight years after ceased activity. American Midland Naturalist, 69(1), 38–68.

FAO. (1997). Soil map of the world. Revised legend, with corrections and updates. Roma.

FAO. (2008). Land use systems of the world - Latin America and Caribbean.

Flueck, W. (2013). Effects of fluoride intoxication on teeth of livestock due to recent volcanic eruption in Patagonia, Argentina. Online Journal of Veterinary Research, 14(4), 167–176. Retrieved from http://www.deerlab.org/Publ/pdfs/68.pdf

Fowler, W. B., & Lopushinsky, W. (1986). Wind blown volcanic ash in forest and agricultural conditions as related to meteorological conditions. Atmospheric Environment, 20(3), 421–425.

Frognerkockum, P., Herbert, R., & Gislason, S. (2006). A diverse ecosystem response to volcanic aerosols. Chemical Geology, 231(1-2), 57–66. http://doi.org/10.1016/j.chemgeo.2005.12.008

Fuchs, S., Birkmann, J., & Glade, T. (2012). Vulnerability assessment in natural hazard and risk analysis: current approaches and future challenges. Natural Hazards, 64(3), 1969–1975. http://doi.org/10.1007/s11069-012-0352-9

Gestsdóttir, H., Baxter, P., & Gísladóttir, G. A. (2006). Fluorine poisoning in victims of the 1783-84 eruption of the Laki fissure, Iceland. Eystri Ásar & Búland – pilot study excavation report. Fornleifastofnun Íslands, Reykjavik. 40pp.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. Science (New York, N.Y.), 327(5967), 812–8. http://doi.org/10.1126/science.1185383

Haddow, G., Bullock, J., & Coppola, D. P. (2013). Introduction to emergency management (5th Ed.). Waltham, MA: Butterworth-Heinemann.

Inbar, M., Ostera, H., Parica, C., & Remesal, M. (1995). Environmental assessment of 1991 Hudson volcano eruption tephra fall effects on southern Patagonia region, Argentina. Environmental Geology, 119–125. Retrieved from http://www.springerlink.com/index/N155558J53T56557.pdf

Jenkins, S. F., Spence, R. J. S., Fonseca, J. F. B. D., Solidum, R. U., & Wilson, T. M. (2014a). Volcanic risk assessment: Quantifying physical vulnerability in the built environment. Journal of Volcanology and Geothermal Research, 276, 105–120. http://doi.org/10.1016/j.jvolgeores.2014.03.002

Jenkins, S. F., Wilson, T. M., Magill, C. R., Miller, V., & Stewart, C. (2014b). Volcanic ash fall hazard and risk: Technical background paper for the UN-ISDR Global Assessment Report on Disaster Risk Reduction 2015. Mln (Vol. 120). Retrieved from http://muse.jhu.edu/content/crossref/journals/mln/v120/120.3contributors.html

Johnston, D. M., Houghton, B. F., Neall, V. E., Ronan, K. R., & Paton, D. (2000). Impacts of the 1945 and 1995-1996 Ruapehu eruptions, New Zealand: An example of increasing societal vulnerability. Geological Society of America Bulletin, (5), 720–726.

Le Pennec, J., Ruiz, G. A., Ramón, P., Palacios, E., Mothes, P., & Yepes, H. (2012). Impact of tephra falls on Andean communities : The influences of eruption size and weather conditions during the 1999 – 2001 activity of Tungurahua volcano , Ecuador. Journal of Volcanology and Geothermal Research, 217-218(August 2006), 91–103. http://doi.org/10.1016/j.jvolgeores.2011.06.011

LEGS: Livestock emergency guidelines and standards. (2014) (2nd Ed.). Warwickshire: Practical Action Publishing. http://doi.org/http://www.livestock-emergency.net/

Leonard, G. S., Johnston, D. M., Williams, S., Cole, J. W., Finnis, K., & Barnard, S. (2005). Impacts and management of recent volcanic eruptions in Ecuador: lessons for New Zealand. GNS Science report 2005/20.

Lyons, J. V. (1986). Agricultural impact and adjustment to the Mount St. Helens tephra fall: a search for analogs. In S. Keller (Ed.), Mount St. Helens: five years later (pp. 423 – 429). Cheney: Eastern Washington University Press.

Martin, R. S., Watt, S. F. L., Pyle, D. M., Mather, T. a., Matthews, N. E., Georg, R. B., Day, J. A., Fairhead, T., Witt, M. L. I. & Quayle, B. M. (2009). Environmental effects of tephra fall in Argentina from the 2008 Chaitén volcanic eruption. Journal of Volcanology and Geothermal Research, 184(3-4), 462–472. http://doi.org/10.1016/j.jvolgeores.2009.04.010

Mercado, R. A., Betram, J., Lacsamana, T., & Pineda, G. L. (1996). Socioeconomic impacts of the Mount Pinatubo eruption. In C. G. Newhall & R. S. Punongbayan (Eds.), Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines. Quezon City: University of Washington Press.

Mileti, D., & Henry, A. J. (1999). Disasters by design: A reassessment of natural hazards in the United States. Washington D. C.: National Academies Press.

Nelson, S., & Sewake, K. (2008). Volcanic Emissions Injury to Plant Foliage. Plant Disease, 47, 1–11.

Neild, J., Flaherty, P. O., Hedley, P., Underwood, R., Johnston, D., Christenson, B., & Brown, P. (1998). Impact of a Volcanic Eruption on Agriculture and Forestry in New Zealand.

Óskarsson, N. (1980). The interaction between volcanic gases and tephra: fluorine adhering to tephra of the 1970 Hekla eruption. Journal of Volcanology and Geothermal Research, 8, 251–266. Retrieved from http://www.sciencedirect.com/science/article/pii/0377027380901079

Phelan, J., Finnegan, D., Ballantine, D., & Zoller, W. (1982). Airborne aerosol measurements in the quiescent plume of Mount St. Helens: September, 1980. Geophysical Research Letters, 9(9), 1093–1096.

Rees, J. D. (1993). Effects on natural and agricultural vegetation. In F. Luhr & T. Simkin (Eds.), Paricutin: The volcano born in a Mexican cornfield (pp. 215–229). Pheonix, Arizona: Geoscience Press, Inc.

Rees, J. D., & Angeles, L. (1970). Paricutin revisited: a review of man's attempts to adapt to ecological changes resulting from volcanic catastrophe. Geoforum, 4.
Rejmanek, M., Haagerova, R., & Haager, J. (1982). Progress of plant succession on the Paricutin Volcano: 25 years after activity ceased. American Midland Naturalist, 108(1), 194–198. Retrieved from http://www.jstor.org/stable/10.2307/2425309

Rossetto, T., Ioannou, I., Grant, D. N., & Maqsood, T. (2014). Guidelines for Empirical Vulnerability Assessment Report produced in the context of the Vulnerability Global Component project. Pavia.

Rubin, C. H., Noji, E. K., Seligman, P. J., Holtz, J. L., Grande, J., & Vittani, F. (1994). Evaluating a fluorosis hazard after a volcanic eruption. Archives of Environmental Health, 49(5), 395–401. http://doi.org/10.1080/00039896.1994.9954992

Salazar, J., Godagnone, R., & Marcolin, A. (1982). Relevamiento integrado de recursos naturales de Rio Negro. S. C. de Bariloche.

Seymour, V. A., Hinckley, T. M., Morikawa, Y., & Franklin, J. F. (1983). Foliage damage in coniferous trees following volcanic ashfall from Mt . St . Helens, 59(2/3), 339–343.

Shoji, S., Nanzyo, M., & Dahlgren, R. A. (1993). Volcanic Ash Soil. Amsterdam: Elsevier Science.

Siffredi, G., & Ayesa, J. (2011). Informe estado de los pastizales en la transecta Bariloche-Onelli (Ruta 23). Bariloche.

Smith, A. M., Coupland, G., Dolan, L., Harberd, N., Jones, J., Martin, C., Sablowski, R., & Amey, A. (2010). Plant Biology. New York: Garland Science.

Smith, K. (2013). Environmental hazards: Assessing risk and reducing disaster (6th Ed.). New York: Routledge.

Smith, W. H., & Staskawicz, B. J. (1977). Removal of Atmospheric Particles by Leaves and Twigs of Urban Trees : Some Preliminary Observations and Assessment of Research Needs. Environmental Management, 1(4), 317–330.

Sneva, F., Britton, C., & Mayland, H. (1982). Mt. St. Helens Ash: Considerations of its fallout on rangelands. Retrieved from http://eprints.nwisrl.ars.usda.gov/1128/1/615.pdf

Sparks, R. J., Aspinall, W. P., Crosweller, H. S., & Hincks, T. K. (2013). Risk and uncertainty assessment of volcanic hazards. In Risk and uncertainty assessment for natural hazards (p. 558). Cambridge: Cambridge University Press.

Spence, R. J. S., Kelman, I., Baxter, P. J., Zuccaro, G., & Petrazzuoli, S. (2005). Residential building and occupant vulnerability to tephra fall. Natural Hazards and Earth System Science, 5(4), 477–494. http://doi.org/10.5194/nhess-5-477-2005

Spence, R. J. S., Zuccaro, G., Petrazzuoli, S., & Baxter, P. J. (2004). Resistance of Buildings to Pyroclastic Flows: Analytical and Experimental Studies and Their Application to Vesuvius. Natural Hazards Review, 5(1), 48–59. http://doi.org/10.1061/(ASCE)1527-6988(2004)5:1(48)

Stewart, C., Horwell, C., Plumlee, G., Cronin, S., Delmelle, P., Baxter, P., Calkins, J., Damaby, D., Morman, S., & Oppenheimer, C. (2013). Protocol for analysis of volcanic ash samples for assessment of hazards from leachable elements.

Sword-Daniels, V., Wardman, J., Stewart, C., Wilson, T., Johnston, D., & Rossetto, T. (2011). Infrastructure impacts, management and adaptations to eruptions at Volcán Tungurahua, Ecuador, 1999-2010.

Sword-Daniels, V., Wilson, T. M., Sargeant, S., Rossetto, T., Twigg, J., Johnston, D. M., Loughlin, C., & Cole, P. D. (2014). Consequences of long-term volcanic activity for essential services in Montserrat: challenges, adaptations and resilience. Geological Society, London, Memoirs, 39(1), 471–488. http://doi.org/10.1144/M39.26

Thorarinsson, S. B., & Sigvaldason, G. E. (1971). The Hekla eruption of 1970. Bulletin of Volcanology, 36(2), 269–288.

Ugolini, F., & Dahlgren, R. (2002). Soil development in volcanic ash. Global Environmental Research, 69–81. Retrieved from http://ns.airies.or.jp/publication/ger/pdf/06-2-09.pdf

Varekamp, J. C., Luhr, J. F., & Prestegaard, K. L. (1984). The 1982 eruptions of El Chichón volcano (Chiapas, Mexico): Character of the eruptions, ash-fall deposits, and gasphase. Journal of Volcanology and Geothermal Research, 23(1-2), 39–68.

Veneklaas, E. (1990). Nutrient fluxes in bulk precipitation and throughfall in two montane tropical rain forests, Colombia. The Journal of Ecology, 78(4), 974–992.

Wardman, J., Stewart, C., & Wilson, T. (2012). Impact assessment of the May 2010 eruption of Pacaya volcano, Guatemala. GNS Science report 2012/09. 85pp.

Wang, B., Michaelson, G., Ping, C.-L., Plumlee, G., & Hageman, P. (2010). Characterization of Pyroclastic Deposits and Pre-eruptive Soils following the 2008 Eruption of Kasatochi Island Volcano, Alaska. Arctic, Antarctic, and Alpine Research, 42(3), 276–284. http://doi.org/10.1657/1938-4246-42.3.276

Watt, S. F. L., Pyle, D. M., Mather, T., Martin, R. S., & Matthews, N. E. (2009). Fallout and distribution of volcanic ash over Argentina following the May 2008 explosive eruption of Chaitén, Chile. Journal of Geophysical Research, 114(B4), 1–11. http://doi.org/10.1029/2008JB006219

Wilson, G., Wilson, T. M., Deligne, N. I., & Cole, J. W. (2014). Volcanic hazard impacts to critical infrastructure: A review. Journal of Volcanology and Geothermal Research, 286, 148–182. http://doi.org/10.1016/j.jvolgeores.2014.08.030

Wilson, T., Cole, J., Cronin, S., Stewart, C., & Johnston, D. (2011a). Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: lessons for recovery. Natural Hazards, 57(2), 185–212. http://doi.org/10.1007/s11069-010-9604-8

Wilson, T., & Kaye, G. (2007). Agricultural fragility estimates for volcanic ash fall hazards. GNS Science report 2007/37. 52pp.

Wilson, T., Kaye, G., Stewart, C., & Cole, J. (2007). Impacts of the 2006 eruption of Merapi volcano, Indonesia, on agriculture and infrastructure. GNS Science report 2007/07. 71pp.

Wilson, T. M., & Cole, J. W. (2007). Potential impact of ash eruptions on dairy farms from a study of the effects on a farm in eastern Bay of Plenty, New Zealand; implications for hazard mitigation. Natural Hazards, 43(1), 103–128. http://doi.org/10.1007/s11069-007-9111-8

Wilson, T. M., Cole, J. W., Johnston, D. M., Stewart, C., Dewar, D. J., & Cronin, S. J. (2009). The 1991 eruption of Volcán Hudson, Chile: impacts on agriculture and rural communities and long-term recovery. GNS Science report 2009/66.

Wilson, T. M., Cole, J. W., Stewart, C., Cronin, S. J., & Johnston, D. M. (2011b). Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. Bulletin of Volcanology, 73, 223–239. http://doi.org/10.1007/s00445-010-0396-1

Wilson, T. M., Stewart, C., Sword-Daniels, V., Leonard, G. S., Johnston, D. M., Cole, J. W., Wardman, J., Wilson, G., & Barnard, S. T. (2012a). Volcanic ash impacts on critical infrastructure. Physics and Chemistry of the Earth, Parts A/B/C, 45-46, 5–23. http://doi.org/10.1016/j.pce.2011.06.006

Wilson, T., Stewart, C., Bickerton, H., Baxter, P., Outes, V., Villarosa, G., & Rovere, E. (2012b). The health and environmental impacts of the June 2011 Puyehue-Cordón

Caulle volcanic complex eruption: a report on the findings of a multidisciplinary team. GNS Science report 2012/20.

Witham, C., Oppenheimer, C., & Horwell, C. (2005). Volcanic ash-leachates: a review and recommendations for sampling methods. Journal of Volcanology and Geothermal Research, 141(3-4), 299–326. http://doi.org/10.1016/j.jvolgeores.2004.11.010

Zheng, S. J. (2010). Crop production on acidic soils: overcoming aluminium toxicity and phosphorus deficiency. Annals of Botany, 106(1), 183–4. http://doi.org/10.1093/aob/mcq134

Chapter Five

Agricultural impact database and post-event impact assessment guidelines for tephra fall events

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5.1 Abstract

Post-event impact assessments (post-EIA) following natural hazard events are a vital source of impact, hazard and vulnerability information used to inform impact and risk assessment models. Increasing the accuracy and robustness of impact and risk assessment models is an important role of science within disaster risk reduction (DRR), as these models often underpin decision making for disaster risk management initiatives. Whilst numerous post-EIAs have been undertaken to assess impacts of tephra fall on agricultural systems, these have been undertaken using several methods, and data has not been collected, recorded or disseminated in a consistent manner. This limits the usability and incorporation into risk assessment tools, such as fragility functions and other quantitative predictive tools. It is a particular problem for volcanic impact science, as there is a brevity of quantitative volcanic impact data available for informing volcanic impact and risk models. This chapter introduces a proposed methodology and guidelines for collection and storage of data from agricultural post-EIA for tephra fall in the form of an agricultural impacts database (AID). The recommended AID concept has been designed to assist in collecting robust, systematic and comparable data, which can be used to inform and refine the derivation of quantitative vulnerability models (such as

fragility functions). Additionally, it also provides templates for data collection during post-EIA for the exposure and pre-event characteristics, the hazard source and properties, the impacts to the exposed agricultural systems, and the management and mitigative response. It is hoped that the AID and associated post-EIA guidelines can be used to document tephra fall impacts in a manner that leads to wider lessons and facilitates DRR.

5.2 Introduction

Tephra fall is the most frequent and widespread product of volcanic eruptions. It can have a variety of impacts to primary industries and cause substantial decreases in the production rate of primary industries (Wilson et al. 2012a). Understanding the impacts of a natural hazard event is vital to informing appropriate risk management strategies (G. Wilson et al. 2014). This involves assessing the characteristics of the hazard (including the intensity of the hazard in space and time), what societal elements are exposed, and what is the societal element's vulnerability to impact from the particular hazard. Such impact assessments can then be used post-event to ensure targeted response and recovery strategies are put in place and aid is allocated in the most effective manner. Additionally, this information can also be used in pre-event risk assessments (where the probability of a particular set of impacts is assessed) to determine areas most at risk of future impacts, and to evaluate the utility of risk reduction strategies (ISDR 2009).

To effectively inform such assessments, a broad range of hazard, exposure and vulnerability data is required. Over the past decade, tephra fall hazard assessment has progressed effectively, supported by decades of rigorous physical volcanology field and laboratory work and the development of complex numerical hazard models and associated databases to inform input parameters. However, there remains a general lack of quantitative volcanic impact data to inform vulnerability and risk models (Jenkins et al. 2014a; Jenkins et al. 2014b). The majority of available volcanic vulnerability information is qualitative in nature and often restricted to a few key case studies. Vulnerability estimates need to be updated and improved to facilitate accurate risk assessments (G. Wilson et al. 2014). Exposure data can be challenging to collect and is often dependent on the types of geospatial data available and accessible within the study area. Finally, vulnerability data is arguably the greatest gap and source of uncertainty in volcanic impact and risk assessments (G. Wilson et al. 2014; Wilson et al. 2012a). There are a small but growing number of field-based quantitative volcanic impact assessments (Chapter 2, 3, & 4) and a handful of laboratory studies (Wardman et al. 2012; G. Wilson et al. 2012) that can inform vulnerability models for agriculture (Wilson & Kaye 2007). But given the broad range of impacts and possible agriculture types at risk from volcanic impacts, a hugely expanded dataset is required for the robust analysis of vulnerability and risk.

One method for addressing this impact and vulnerability data deficiency has been the use of post-event impact assessments (Post-EIA) to record volcanic impacts (Jenkins et al. 2014a). Post-EIA's have been used after volcanic events as a vital source of impact, hazard and vulnerability information to inform impact and risk assessment models (Cook et al. 1981; Sneva et al. 1982; Sword-Daniels et al. 2011; Wilson et al. 2011; Wilson et al. 2007). Increasing the accuracy and robustness of impact and risk assessment models is an important role of science within disaster risk reduction (DRR), as these models often underpin decision making for disaster risk management initiatives. Whilst numerous post-EIAs have been undertaken to assess impacts of tephra fall on agricultural systems, these have been done using several methods, and data has not been collected, recorded or disseminated in a consistent manner. This makes it challenging to effectively incorporate the data into risk assessment tools, such as fragility functions and other predictive tools. This further exacerbates the issue with the lack of quantitative volcanic impact data available for informing volcanic impact and risk models.

Post-EIA after volcanic events have been undertaken following numerous eruptions in recent years (Baxter et al. 2005; Blong 1984; Cronin et al. 1997; Jenkins et al. 2014b; Sword-Daniels et al. 2011; Wilson et al. 2007; Wilson et al. 2011; Wilson et al. 2012b), with the focus on data gathering after an event to provide lessons for future worldwide eruptions beginning with the 1980 Mt St. Helens eruption (Cook et al. 1981; Dale et al. 2005; Lyons, 1986; Sneva et al. 1982). Issues with the variety of data types have thus far restricted the integration of recent post-EIA data into risk and vulnerability assessments, as has occurred in other fields – notably earthquake engineering (Rossetto et al. 2013; Rossetto et al. 2014).

To address this deficiency, this chapter introduces an agricultural impacts database (AID) related to tephra fall events which is intended to promote: 1) a more consistent approach during post-EIA campaigns; 2) an increase in the amount of data collected; 3) an increase in the quality of data and a more simple means to incorporate data into risk and vulnerability assessments; 4) easier comparative ability between different eruptions and regions. Importantly, the creation of the AID aims to assist in the refinement of fragility functions for tephra fall hazards. Fragility functions show the probability of a certain impact or damage state being reached at a particular hazard intensity metric (HIM). For tephra fall these are usually developed using tephra thickness as the HIM (Jenkins et al. 2014b). The AID has been proposed to provide an evolving dataset for the continued refinement of agricultural fragility functions (Chapter 6). This ensures that the latest post-EIA information will be integrated into these functions, increasing their accuracy and range of applicability.

This chapter also presents a series of guidelines for an agricultural post-EIA. These include guidelines for site selection, the establishment of longitudinal studies, sampling recommendations, and interview questions. These guidelines are based on the field experience of the New Zealand Volcanic Impact Study Group (VISG) (Daly & Johnston 2015), with the intention of collecting the necessary data to facilitate the refinement of risk and vulnerability assessments. Although these guidelines are not truly universal and will need to be adapted based on the local areas protocol and logistics, they do provide a starting point for a series of questions and research steps that facilitate data entry into the AID.

5.3 Agricultural Impacts Database (AID)

5.3.1 Proposed database design

The AID was designed in order to facilitate the accurate and consistent recording of information collected during post-EIA, in a system that can be shared and added to as new events occur. It was also planned to allow risk and vulnerability assessments to be created and refined using the information and lessons from previous events contained within the AID. To fulfil these aims it is recommended that the database covers four main components, each made up of numerous tables (described in detail in the following sections) (Fig. 5.1):

- The exposure and pre-event characteristics: including the seasonality and pre-existing farming conditions within the affected area.
- The hazard source and properties: including the properties of the eruptive vent, the distribution, and the physical and chemical properties of the tephra deposit.
- The agricultural impacts: including any changes in soil fertility, as well as damage and losses to pastoral, horticultural, and forestry agriculture.
- The agricultural sector response: including details of evacuations, government aid, and mitigation measures employed.

5.3.1.1 Exposure and pre-event characteristics

The characteristics of the agricultural system prior to the tephra fall will, along with the hazard properties, determine the impacts that occur. It has been established in previous case studies that the vulnerability of an agricultural system is influenced by many factors including the climate (Wilson et al. 2011), pre-existing soil chemistry (Cronin et al. 1997), animal and vegetative health (Blong, 1984; Cook et al. 1981), and the access to machinery for cultivation, irrigation and/or tephra removal (Wilson et al. 2007). As the aim of the database is to aid in the development of forecasting and risk assessment tools, it is vital that these sources of vulnerability are captured within AID.

Vulnerability characteristics should be recorded in the AID in the following data tables and fields:

- Climate characteristics table: This records the climatic zone using the Köppen classification system (Peel et al. 2007). The table also contains fields that quantify the annual and seasonal precipitation levels and the dominant wind direction.
- Land characteristics table: This table primarily registers the soil type and the main agricultural activities that occur within each affected region.
- Agricultural assets table: This allows the farm assets (irrigation, animal shelter, feed stores, livestock/crop diversity, machinery for cultivation/tephra removal) within a region to be estimated using a scoring system (Table 5.1). These values are then added to give a vulnerability index, where zero is the most resilient and 15 is the most vulnerable.
- Pre-eruption soil chemistry table: In order to assess the impact that tephra has on soil fertility, a baseline of soil fertility indicator values needs to be recorded and accessible.

Table 5.1: Vulnerability scoring scheme applied to define the relative availability of farm improvement assets in affected regions.

Descriptor	Approximate % occurrence	Vulnerability Score
Rare	0-25	3
Occasional	>25-50	2
Frequent	>50-75	1
Common	>75-100	0

The aim of the vulnerability scale is to provide a rapid assessment of the relatively vulnerability of the various data entries, by assigning a simple numeric scale users can identify points where high vulnerability may have contributed to greater thank expected losses. Information on the different relative vulnerabilities can also be found by comparing applicable risk assessment tools, however this is relatively complex compared to having the vulnerability index field attached to each AID entry.

Unlike the hazard and impact data tables, the vulnerability tables can be assessed and inputted into the database prior to the eruption. This data collection is especially useful in areas where the risk of a volcanic eruption is high, and areas of vulnerability could therefore be readily identified prior to the event.

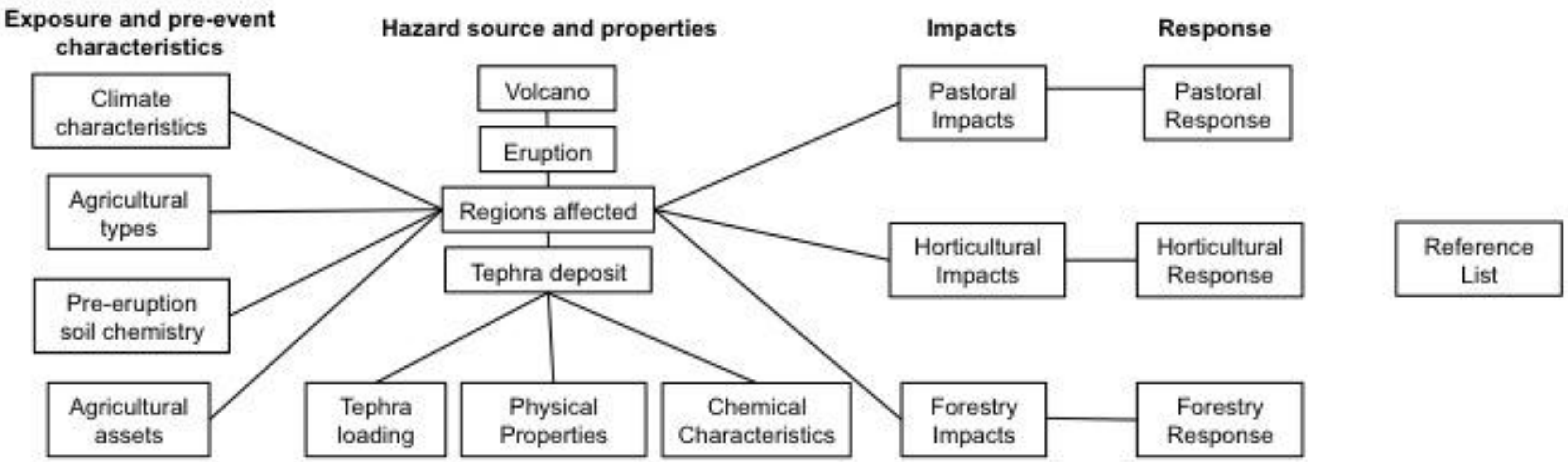

Figure 5.1: Conceptual diagram of AID design showing the information flow from pre-event vulnerability through to eruption, impacts and response.

5.3.1.2 Hazard source and properties

Volcano information was derived from the Smithsonian Institution's Global Volcanism Program (GVP) database (Siebert et al. 2010). This database is an internationally recognised source of information on the occurrence of Holocene volcanoes. It contains >1,500 volcanoes that are catalogued by their official GVP name and unique volcano number. These names and numbers are ideal for identifying the volcanoes compiled in the AID. The GVP information was used to create the volcano table within the proposed AID, and also includes location information (latitude, longitude), the type of volcano, and elevation.

In addition to the volcano table, there is also a proposed table that records the properties of the individual eruption being assessed. This includes the start and end date of the specific eruption, the Volcanic Explosivity Index (VEI) value, and the type of eruption. A three letter, two number, eruption specific identifier is also assigned to each eruption. This is based on the volcano name and the year for the eruption, for example the 1995 Ruapehu eruption is coded as RUA95. The GVP volcano number links the eruption table to the volcano table in a one to many relationship (as one volcano can be responsible for many eruptions).

As the AID currently only aims to contain information about the impacts due to tephra fall, only tephra fall hazard data is included. This is recorded in the tephra deposit table and includes the following fields:

- The extent of the deposit (km^2).
- The tephra volume (m^3).
- The maximum column height (km).
- The bulk density of the deposit (g/m^3).
- The start and end date of the main tephra falls associated with the eruption.
- The number of eruptive units and the median grain size of each (μm).

If isopach maps and detailed grain size distributions become available, these may be attached to the AID entry.

5.3.1.3 Agricultural impacts

The agricultural impacts data recommended for input into the AID can be divided into two main types. The first type is data that can be collected in the field through observation and semi-structured interviews with agriculturalists. This data is primarily qualitative in nature but can include quantitative data such as production loss percentages and number of livestock deaths. The second way of inputting impact data into the AID is through a quantitative impact metric. This allows for overall impacts between events to be compared and is usually in the form of a damage or impact state. Damage or impact states categorise impacts to assets based on a number of defined states, which each have a qualitative description of impacts and often a quantitative measure (such as percentage damage, repair cost). Currently, the proposed AID has been developed to be used with the damage/production states (DPS) presented in Chapter 6. However, this database could be adapted to include other quantitative impact assessment measures during further development. Assigning a DPS to each AID entry means that the AID information can easily be used to refine proposed fragility functions (Chapter 6). This will allow for the continued refinement of these tools. Additionally, as a more diverse (different climates, farming styles and intensities, etc.) dataset is acquired, more regionally specific fragility functions can be developed. By including a field to input a DPS value, in addition to fields capturing qualitative impact data, this requires users to provide a quantitative assessment of the impact intensity. It is this quantitative assessment that allows for more accurate, numeric risk assessment tools to be developed.

The impacts tables are central to the AID and are divided into pastoral, horticultural, and forestry impact tables. This mirrors the division used to create the DPS schemes. DPS are used to categorise the impacts to agricultural systems after tephra fall. They range from DPS0 (no damage or production changes) to DPS4 (high damage, retirement of land and 100% production losses), and each contains a description of the damage and effects on production. A full explanation of the development and results of these can be found in Chapter 6. A DPS value is applied at the end of each data entry for impacts to summarise the detailed impact data contained within the row. These are assigned based on observations taken in the field, and data given on production changes. These impact details differ for each of the three main sub-sectors and are summarised in Table 5.2.

Table 5.2: Impact data fields for agricultural sub-sector tables.

Pastoral	Horticultural	Forestry
ID Eruption Tephra thickness (mm) Region/province Regional code Regional scale data Farm scale data Farm size (ha)		
Dairying Animal types Animal Deaths Percentage Animal Deaths Primary Cause Gastrointestinal Blockages Fluorosis Tooth Abrasion Starvation Dehydration Eye Irritation Tephra Weighing animals Down Fertility Issues Fleece Damage Reduction in Fleece Price (%) Milk Reduction (%) Water Supply Issues Pasture Losses Farm Machinery Corrosion Visual estimation of pasture health	Primary crop type Secondary crop type Smothering Acid burns Photosynthesis prevented Abrasion to fruits Total burial Other details Water supply issues Crop breakages	Tree breakages Age of broken trees (yrs) Trees killed Age of trees killed (yrs) Disruptions to harvesting Disruption details Damage to equipment Accessibility issues Visibility issues
Tephra Remobilisation Remobilisation Type Economic Loss in Agriculture Sector (US$ at time of eruption) Positive Impacts Seasonal vulnerability		
Max DPS reached	Root DPS Fruit DPS Tree Fruit DPS Leafy DPS Cereal DPS Viticulture DPS Paddy DPS	Max DPS reached
Date Collected Investigator Reference code Data quality score		

In addition to a quantitative measure of impacts for each of the impact rows created, the other vital input is a hazard intensity metric (HIM) at each impact site. This is a measure of the severity of the hazard at a particular location and can be collected in the field during post-EIA (if the deposit is still fully preserved) or from other sources of information such as isopach maps or reports. For tephra fall hazards this is usually tephra thickness in millimetres (and where possible loading in kg/m^2). The inclusion of HIM and quantitative impact measures in the AID is essential as they provide the numerical inputs that allow qualitative risk and vulnerability assessments to be undertaken. Currently, the agricultural impacts tables directly relate to the exposure and pre-event tables (Section 5.3.1.1) on climate, land, agricultural assets, and pre-eruption chemistry by region in a one (pre-eruption table) to many (impacts tables) relationship. This allows for comparison between impacts and sources of vulnerability that could have been identified pre-event.

5.3.1.4 Agricultural sector response

It is important that the variation in management response is also recorded in the AID. This will allow for the identification of successful mitigation schemes and management decisions. The differences in response could also be used to explain some differences in impacts, for example in an area where livestock were evacuated (recorded in the response table) there is likely to be fewer animal deaths (recorded in the impacts table) than expected. Another application of the response table data could be to compare the production change (in the impacts table) to the amount of financial assistance available. This information could then evaluate the effectiveness of monetary aid (i.e., was the financial aid cost effective at reducing losses).

The agricultural sector response table contains the following fields and information:

- The number and nature of evacuations of both people and livestock, including fields for any voluntary evacuations recorded. The length of time people and livestock remained evacuated from the area is also included.
- The approximate number of livestock sold due to the tephra fall.
- The reduction in price of agricultural products due to the livestock market being flooded with animals and/or the decrease in the quality of products.

- Details of the mitigation methods employed by farmers such as:
    - Topsoil cultivation
    - Fertilisation
    - Windbreaks and shelter construction
    - Irrigation
    - Tephra removal

The date that this information is collected is also significant, as it is likely that the response will vary over time in the weeks and months after the eruption. The recommended AID structure allows multiple data entries to be made at different dates as the situation evolves.

5.3.1.5 Data quality

It is likely that the data inputs into the AID are not going to be of the same quality. Therefore, it is important to incorporate a measure of this relative quality so that any users of the material or developers of future risk assessment tools are aware of the possible data limitations. In order to communicate these differences a scoring system based on the source of the information is proposed (Table 5.3).

Table 5.3: Data quality scoring system used with the AID.

Data quality score	Data description
0	Primary data from newspapers, websites, public statements
1	Qualitative statements from farmers and agriculturalists in the area
2	Emergency management/ agricultural agency/ government reports
3	Qualitative post-EIA undertaken by scientists
4	Quantitative post-EIA undertaken by scientists

The references for each data entry should be coded within a reference number field that links to an entry in the central reference table in a many-to-one relationship. This, along with the data quality score, allows for transparency in data reliability.

5.3.2 Discussion

5.3.2.1 Database applications

The AID could be used:

- To collect information from past and current post-EIA in a standardised, user-friendly format.
- To draw comparisons between events and extract lessons that the relationships demonstrate.
- To focus on vulnerability and exposure through to impacts and response. The AID can be added to progressively throughout an event. Additionally, impacts can be searched based on different vulnerability characteristics and seasonal occurrences, to identify patterns in vulnerability and resultant impacts.
- In the production of accompanying post-EIA guidelines (Section 5.4) which when used in field will gather sufficient information to create an AID entry. This creates a cycle of information inputs and assessment refinements, as the AID informs the post-EIA guidelines and vice versa.
- As part of an information repository that can be used to identify pre-eruption characteristics in agricultural systems that lead to vulnerability and resilience.
- To refine risk assessment and forecasting tools such as fragility functions. As more impact and associated hazard and vulnerability information becomes available, increasingly sophisticated and robust predictive tools can be developed.

The data taken from the proposed AID in its existing form and used to create the fragility functions (in Chapter 6) is shown in Figure 5.2. Whilst the dataset is far from complete and its representative nature unknown, the AID provides the largest complete agricultural impacts from tephra fall dataset. This allowed for greater empirical data input and the division of agricultural types and vulnerabilities, compared to previous agricultural and tephra fragility functions (Wilson & Kaye, 2007).

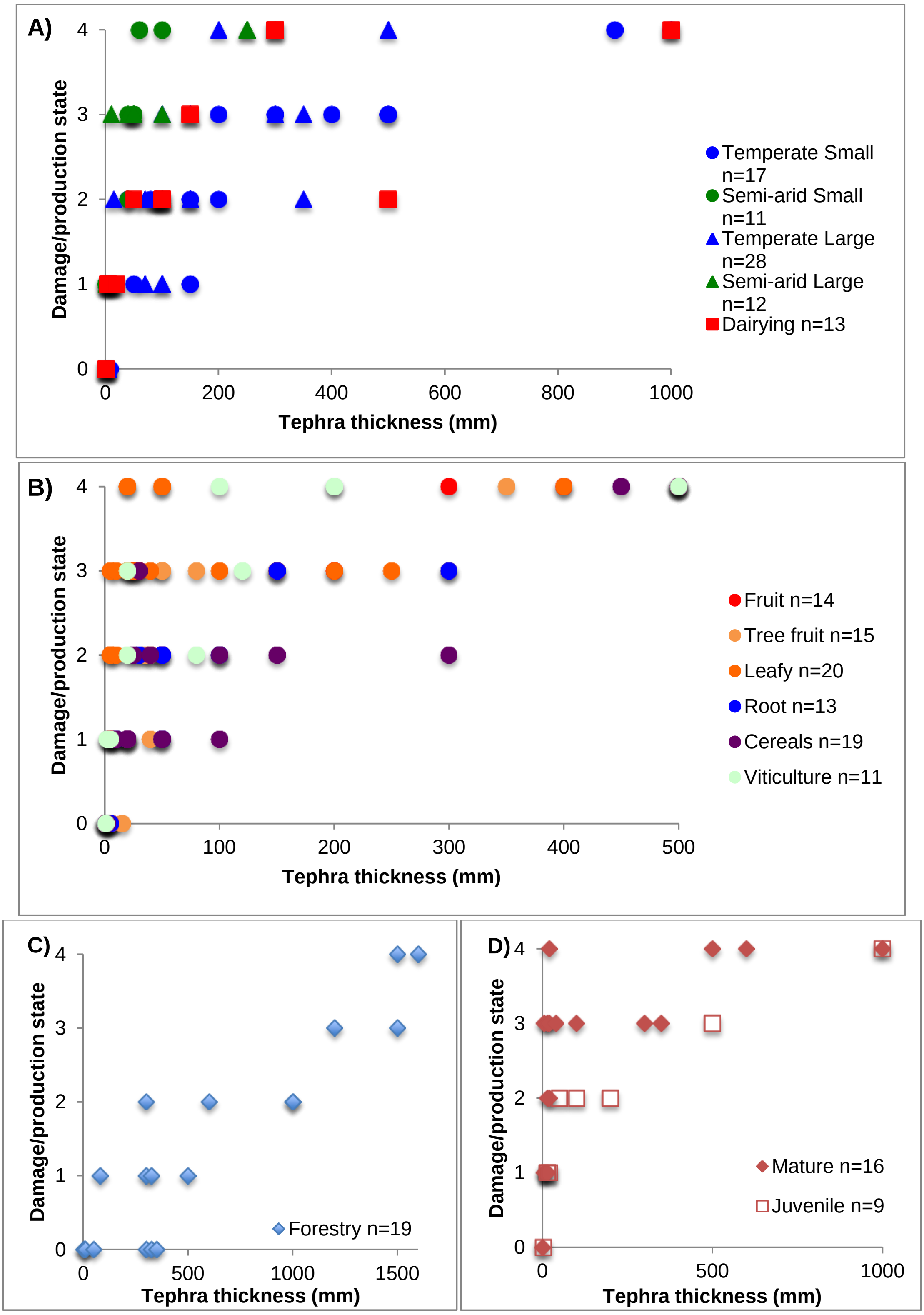

Figure 5.2: Graphs showing the damage/production state and tephra thickness data taken from the AID and used in fragility function development for A) pastoral agriculture; B) horticulture; C) forestry; and D) rice paddy farming. The number of points is indicated in the key of each.

5.3.2.2 Limitations and improvements needed

The proposed AID structure is currently confined to usage within one research group (New Zealand VISG) and the format has not been widely tested with other interested groups. The AID is intended to become open access with further development and the creation of a web-based format, however this is the most important current limitation of the AID. Additionally, the complexity and level of detail required to complete some of the fields may discourage participation, although it is acceptable for an entry to contain some incomplete fields. Conversely, there may be some instances where the AID does not contain a field that captures very rare or anomalous impacts. However, the inclusion of a text-formatted comment field does provide some opportunities for this. Similarly, the binary nature of some of the fields, such as region code, occurrence or absence of some impacts, and data quality may not capture some of the subtleties in the data. Care has been taken to avoid losing this detail with the inclusion of a large number of diverse impact fields.

It is also possible that the database could be extended to include an overview of other volcanic hazards (lava flows, lahars, ballistics, gas, etc.). However, as the impacts recorded in the proposed AID are currently restricted to those only caused by tephra fall, the impacts sections would need to be revised accordingly with any further hazards being introduced.

Currently, the AID represents a template for database development rather than a functional, user interface. It does, however, identify the information required to provide consistent, high quality inputs to continue the development of robust risk assessment tools, such as fragility functions.

5.4 Post-event impact assessment guidelines

5.4.1 Rationale

Standardised guidelines for the collection of post-EIA data will allow for a higher resolution and quality of data to be collected. The guidelines can be adopted for a range of different scenarios, and will allow for improved consistency between different post-EIA groups and locations. Numerous teams can then assess the same event across the tephra depositional zone using the same guidelines, generating straight-forward comparisons between different events. Additionally, the creation of standardised guidelines will ensure that the information necessary to create and refine risk and vulnerability models is collected during post-EIA. This will be achieved by tailoring the post-EIA guideline questions to ensure that each of the AID fields can be filled in. Whilst specific details about each soil and/or vegetation sample taken are not included within the AID, overall changes in soil and vegetative health are. Therefore, it is important that individual sampling methods are included within the post-EIA guidelines.

5.4.2 Proposed guidelines

The following sections describe the post-EIA assessment guidelines developed for agricultural settings after tephra fall events.

5.4.2.1 Site Identification

In order to create a database of information from the emergency and impact phase through to mitigation and response, suitable study sites need to be selected early on in the process. These should target:

- Intensity - A range of tephra thicknesses/loadings
- Coverage - representative coverage along the tephra plume
- Diversity - Focus on agriculturally productive sites that cover a range of sectors (e.g., pastoral, dairying, horticultural)
- Accessibility - Sites where access is allowed and ethics requirements have been met (these will depend on the target area and the home institute or organisation of the impact assessment team)
- Remobilisation - Target any farms that are vulnerable to remobilisation
- Differences in resilience - Low resilience and high resilience sites (e.g., sites with a large number of built and mechanical assets vs. those without)

Information on each of these site characteristics needs to be recorded.

5.4.2.2 Site Characteristics

At each study site a GPS location, the date and time and a photo with scale need to be recorded. Additionally the following site information needs to be documented:

- Farm type
- Farm ownership/management
- Operating company (if different from owners)
- Closest town or city
- Latitude, longitude and distance from volcano (can be retrospectively calculated)
- Weather at the time of the visit

5.4.2.3 Tephra accumulation

Tephra thicknesses and loading need to be measured and sampled according to International Volcanic Health Hazard Network guidelines (IVHHN 2010), with the aim of completing the tephra leachate testing protocol (outlined in Stewart et al. 2013) and undertaken for the Cordón Caulle tephra in Chapter 3. Ideal sample sites are areas that are intensively farmed, but have not been disturbed since the tephra deposition.

5.4.2.4 Vegetation Impacts

Visual assessment of vegetation cover and health will need to be conducted at the same sites from initial deposition through to recovery phase. It is therefore important that this is done consistently.

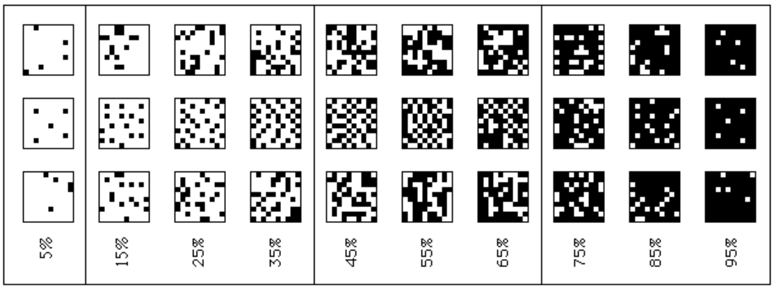

Figure 5.3: Chart for estimating the percentage of pasture cover (adapted from Shepard 2009).

The percentage of pasture cover that is visible above the tephra deposit should be recorded, using the chart as a guide (Fig. 5.3).

Another useful visual observation is that of vegetation health using the following qualifiers (McLaren & Cameron, 1996).

- **Good Condition:** 95% green leaf herbage, ≥ 60% legume cover, with ≤5% dead matter.
- **Moderate Condition:** 75-80% green leaf herbage, 20-40% legume cover, with 20-25% dead matter.
- **Poor Condition:** Pasture has ≤50% leaf herbage with little or no legumes, and ≥50% dead matter.

For areas that will likely become longitudinal study sites (easily accessible, good relationships formed with owner), it is useful to take a vegetation sample.

Taking a pastoral sample (J. White & Hodgson, 1999):

- Select sites that are representative of the area, but that have not had heavier stock or vehicle traffic.
- Take an additional GPS location if needed and a photograph of the site.
- Record the type of vegetation and grazing on the area, also its aspect (flat land, slope or ridge).
- Walk across the target pasture (usually an area spanning 100m diagonally), every three steps stop and cut with scissors three small samples of pasture to ground level (one sample adjacent to each foot, and one midway between your step).
- About 100g of pasture is an ideal sample size.
- Place in brown paper bag and label.
- Dry at room temperature.

5.4.2.5 Soil Sampling and Health

As for vegetation assessment the health and nutrient status of the soil will be an important feature of longitudinal studies. Whilst a visual estimate of soil health can be used (such as Shepard 2009), it will likely be easier to take a sample and complete analysis later. These sampling guidelines are proposed to allow for the suite of soil fertility tests (as undertaken in Chapter 3) to be undertaken.

Taking a soil sample (Brown et al. 2004):

- Select sites that are representative of the area, but that have not had heavier stock or vehicle traffic.
- Take an additional GPS location if needed and a photograph of the site.
- Record the type of vegetation and grazing on the area, as well whether on flat land, sloping land or on a ridge.
- Note if there is any evidence of fertilisation, cultivation and/or irrigation.
- Remove as much tephra and vegetation from above the soil sample as possible.
- Collect 5-10 samples of soil down to 7.5 cm depth in a zig zag pattern across the chosen site (usually samples 1 m apart).
- Use a clean stainless steel trowel for taking samples.
- Combine the soil samples into one plastic bag (to make approximately 500g) and label.
- Do not allow samples to remain in moist dry conditions.

5.4.2.6 Recovery Studies

In the weeks and months after the initial tephra fall key sites should be revisited. These should be the sites that best fit the site selection criteria listed in Section 4.2.1, and also be sites where farm owners and workers are willing to cooperate.

For these sites specific information needs to be collected on:

- What mitigation methods were employed?
- Which sections of the farm were targeted?
- When was any mitigation undertaken?
- What fertiliser mix was used?
- What improvements to production have farmers seen?
- Are there areas of the farm that had not been treated that can be used as a baseline?
- Are farmers willing to provide estimates of the costs of any measures employed?
- How has production changed compared to pre-eruption, immediately post-eruption and subsequent visits?

Sites where this information is available should have the vegetation and soil observations and sampling done at each visit.

5.4.2.7 Interview Questions

Ideal interview participants include:

- Farm owners/managers
- Farm workers (with permission from managers)
- Regional council managers
- Rural agencies (Rural Support, Rural Women, Federated Farmers, Dairy NZ etc.)
- Agricultural scientists
- Veterinarians

At all sites where farmers/agricultural managers are available to be interviewed the following is a guide that can be used to conduct semi-structured interviews, using the questions detailed in Table 5.4.

Table 5.4: Questions proposed for a post-EIA for various agricultural types after tephra fall.

General Questions
Pre-eruption conditions What were the weather conditions at the time? Were there any preparedness plans in place for tephra fall events pre-eruption? What warnings were given before the tephra fall?
Tephra fall hazard Amount and description of tephra fall in area? Duration of tephra fall? Was any warning received? Wind/water remobilisation observed? Was tephra compacted?
Impacts on household How did it affect your day-to-day life? Were there impacts to transport networks? Was there any affect on human health? Were water supplies impacted?

Building damage? Power supply disruption? Any communication issues? Has failure or disruption of other infrastructure caused any issues?
Response How was tephra cleaned-up? Stabilization techniques? Tephra dump locations? Mitigation techniques employed? Any evacuations? What emergency information did authorities give? How was this communicated?
Pastoral Questions
Pre-eruption conditions Farm size? Annual production? Animal numbers? What type of feed does the farm primarily use? What is the water source? What fertilisation, irrigation, cultivation is undertaken on the farm? What farm buildings are used? What is the size/construction type of these?
Impacts What farm activities (such as fertilisation, irrigation, cultivation) were disrupted by the tephra fall? Was there damage to any farm equipment or machinery due to the tephra fall? Was there any damage to any farm buildings? Changes in soil fertility? Changes in pasture yield/health? Any treatments for plants and to protect animals used? Animal losses sustained? What supplementary food has been used? Estimated production losses? Economic losses? How has the tephra fall changed the way the area is farmed?

Were any soil fertility tests undertaken post-eruption? Were these different from pre-event results?
Response Were any animals evacuated? Details of animal movement What steps were taken to try and protect animal health? Were supplementary feed supplies needed? What kind? How much? Was cultivation of the tephra fall into the topsoil attempted? Was tephra removal attempted? Was any fertiliser applied in response to the tephra fall? What assistance from authorities was given? What advice was given? What help would have been useful?
Horticultural Questions
Pre-eruption conditions Farm size? Annual production? Crop type and amount? Primary and secondary crop types? Are greenhouses used? What size/construction type are these? What is the water source? What fertilisation, irrigation, cultivation is undertaken on the farm?
Impacts Did greenhouses or farm structures suffer any damage? What farm activities (such as fertilisation, irrigation, cultivation) were disrupted by the tephra fall? Was there damage to any farm equipment or machinery due to the tephra fall? Changes in soil fertility? Any change in the production of crops? Any discolouration, burns or abrasion of vegetation? Any breakages of vegetation? Any abrasion to farm machinery? What changes to normal farm operations have been made? Estimated production losses? Economic losses?

Were any soil fertility tests undertaken post-eruption? Were these different from pre-event results?
Response Was cultivation of the tephra fall into the topsoil attempted? Was tephra removal attempted? Was any fertiliser applied in response to the tephra fall? Were additional shelter belts/greenhouses erected? What assistance from authorities was given? What advice was given? What help would have been useful?
Forestry questions
Pre-eruption conditions Farm size? Annual production? Proportion of mature/juvenile trees? Normal operations prior to the tephra fall? Approximate value of timber?
Impacts Any tree breakages? In what age group were these trees? Seedling losses? Was access by road disrupted? Was there any damage or abrasion to harvesting or transport machinery? Estimated production losses? Economic losses? Were any soil fertility tests undertaken post-eruption? Were these different from pre-event results?
Response What clean-up operations were required to resume normal harvest? Was tephra removal attempted? Was replanting necessary? What assistance from authorities was given? What advice was given? What help would have been useful?

Additionally, collecting any information or observations made by farmers concerning disruption to any interdependent infrastructure is vital.

5.4.3 Field application

The exact method and application of the post-EIA guidelines will be dependent on the location, specific trip aims, and the logistical considerations of the trip. Questions may need to be modified for translation purposes or added to suit differing assessment goals. However, the above guidelines do provide a starting point and contain the information required to input a complete entry into the AID.

5.4.3.1 Timing of assessment

The timing of the post-EIA can have a large influence on the amount, type, and accuracy of information collected. It is important that the date information is recorded to acknowledge the possible influence the time since the eruption could have on the data. This is especially important when considering agricultural impacts, as unlike many infrastructure sectors such as electricity where impacts such as flashover can be near instantaneous with the tephra fall (Wardman et al. 2012), agricultural impacts tend to only fully manifest over weeks to months after the event (Cronin et al. 1997; Wilson et al. 2011). More subtle effects such as chronic fluorosis in livestock, or effects on fertility, may take even longer to manifest (months to years) (Livesey & Payne 2011). This means that agricultural post-EIA may be best undertaken many months after an eruption. However, any decision to wait for impacts to manifest must be balanced with the possibility that some impact information may have been lost or details forgotten if a post-EIA is undertaken too late. Whilst there is no correct time to undertake the assessment, the New Zealand VISG has found that when analysing agricultural impacts 6 months to 2 years after the initial tephra fall appears to be an ideal time window for assessment (Wilson et al. 2014).

5.4.3.2 Eruption/event selection

As with the timing of post-EIA, the selection of which tephra fall events to assess is dependent on a variety of complex factors. These include the time of the eruption, and financial considerations related to travel and field deployment. However, consideration also needs to be given to the research goals and lessons required. For example, some groups wanting to extract information for application to a specific agricultural area may want to select analogous volcanic events, environmental settings, and/or agricultural methods, in order to gain maximum benefit from a post-EIA. Conversely, due to the rarity of large tephra fall events, a well-resourced team may wish to respond to numerous diverse events.

The post-EIA guidelines presented here were designed to be adaptable to any tephra fall event affecting agricultural systems. However, the ability to collect data for all guidelines may be limited in some areas (e.g., where not all types of agriculture exist).

5.4.3.3 Personnel requirements

A range of interested parties could use the post-EIA guidelines including: agricultural agencies, agricultural researchers and scientists, local municipal and council staff, hazard and disaster researchers, and emergency management and civil defence/protection staff. Ideally, a multidisciplinary team (i.e., emergency managers, agricultural scientists, veterinarians, etc.) would be formed with the aim of using the post-EIA guidelines at multiple sites across a transect of the depositional area.

5.4.3.4 Emergency management information needs

The post-EIA and recommended AID fields represent the ideal information requirements that allow for a full holistic understanding of the agricultural vulnerability, impacts, and response. However, it is likely that for many events it will not be possible to assess every recommended post-EIA guideline question and sample. When considering immediate emergency management information needs, understanding the distribution of the tephra deposit and the impacts to each agricultural sector would be the most vital. Information on response measures, specific exposure and vulnerability characteristics of farms, and the chemical impact on soil and vegetation are less important information fields during the initial emergency response period. The post-EIA guidelines can be shortened to only include vital response information initially, however only the full set of questions and a comprehensive AID entry will allow for the refinement of predictive models.

5.5 Summary

The proposed AID provides a method of collecting and compiling information on agricultural impacts due to tephra fall and the pre-eruption vulnerability characteristics and post-eruption response. This is important as this information can be used to identify areas where greater resilience can be built (by comparing vulnerability characteristics with impact data), as well as evaluating the most beneficial management actions and response measures (by comparing response to impact data). The AID will also allow for comparisons between regions within an event as well as across different tephra fall events. This information is also valuable when developing impact-forecasting tools such as fragility functions. The systematic nature of the dataset will lead to the development and refinement of fragility functions that better account for sources of vulnerability and resilience.

Additionally, the need for high quality, consistent post-EIA information to inform and refine risk models, has led to the establishment of post-EIA guidelines. A range of scientist-led teams in diverse areas can use these after tephra fall events. The guidelines also facilitate the transfer of any data collected into the AID, further strengthening the dataset. Overall, both the AID and the post-EIA guidelines for agriculture are tools that will help further the understanding of tephra risk, aid the development of forecasting tools, and assist in the advancement of disaster risk reduction strategies.

5.6 References

Baxter, P. J., Boyle, R., Cole, P., Neri, A., Spence, R., & Zuccaro, G. (2005). The impacts of pyroclastic surges on buildings at the eruption of the Soufriére Hills volcano, Montserrat. Bulletin of Volcanology, 67(4), 292–313. http://doi.org/10.1007/s00445-004-0365-7

Blong, R. J. (1984). Volcanic hazards: A sourcebook on the effects of eruptions. Sydney: Academic Press.

Brown, J. R., Crocker, D. K., Garrett, J. D., Hanson, R. G., Lory, J. A., & Nathan, M. V. (2004). Soil test interpretations and recommendations handbook.

Cook, R. J., Barron, J. C., Papendick, R. I., & Williams, G. J. (1981). Impact on agriculture of the Mount St. Helens eruptions. Science (New York, N.Y.), 211(4477), 16–22. http://doi.org/10.1126/science.211.4477.16

Cronin, S. J., Hedley, M. J., Smith, R. G., & Neall, V. E. (1997). Impact of Ruapehu ash fall on soil and pasture nutrient status 1. October 1995 eruptions. New Zealand Journal of Agricultural Research, 40(3), 383–395. http://doi.org/10.1080/00288233.1997.9513260

Dale, V., Swanson, F., & Crisafulli, C. M. (2005). Ecological responses to the 1980 eruptions of Mt. St. Helens. Springer.

Daly, M., & Johnston, D. (2015). The genesis of volcanic risk assessment for the Auckland engineering lifelines project: 1996–2000. Journal of Applied Volcanology, 4(7), 1–17. http://doi.org/10.1186/s13617-015-0027-9

International Volcanic Health Hazard Network. (2010). IVHHN ash sample collection procedures.

ISDR. (2009). 2009 UNISDR Terminology on Disaster Risk Reduction. Geneva, Switzerland.

Jenkins, S. F., Spence, R. J. S., Fonseca, J. F. B. D., Solidum, R. U., & Wilson, T. M. (2014a). Volcanic risk assessment: Quantifying physical vulnerability in the built environment. Journal of Volcanology and Geothermal Research, 276, 105–120. http://doi.org/10.1016/j.jvolgeores.2014.03.002

Jenkins, S. F., Wilson, T. M., Magill, C. R., Miller, V., & Stewart, C. (2014b). Volcanic ash fall hazard and risk: Technical background paper for the UN-ISDR Global Assessment Report on Disaster Risk Reduction 2015. Retrieved from http://muse.jhu.edu/content/crossref/journals/mln/v120/120.3contributors.html

Livesey, C., & Payne, J. (2011). Diagnosis and investigation of fluorosis in livestock and horses. In Practice, 33(9), 454–461. http://doi.org/10.1136/inp.d6078

Lyons, J. V. (1986). Agricultural impact and adjustment to the Mount St. Helens ashfall: a search for analogs. In S. Keller (Ed.), Mount St. Helens: five years later (pp. 423 – 429). Cheney: Eastern Washington University Press.

McLaren, R. G., & Cameron, K. C. (1996). Soil Science. Melbourne: Oxford University Press.

Peel, M. C., Finlayson, B. L., & Mcmahon, T. A. (2007). Updated world map of the Koppen-Geiger climate classification. Hydrology and Earth Systems Sciences, 11, 1633–1644.

Rossetto, T., Ioannou, I., & Grant, D. N. (2013). Existing Empirical Fragility and Vulnerability Relationships: Compendium and Guide for Selection. Pavia, Italy.

Rossetto, T., Ioannou, I., Grant, D. N., & Maqsood, T. (2014). Guidelines for Empirical Vulnerability Assessment Report produced in the context of the Vulnerability Global Component project. Pavia.

Shepard, G. (2009). Visual soil assessment. Palmerston North: Horizons Regional Council.

Siebert, L., Simkin, T., & Kimberley, P. (2010). Volcanoes of the world: an illustrated catalog of holocene volcanoes and their eruptions (Third Ed.). Washington D. C.: Smithsonian Institute, University of California Press.

Sneva, F., Britton, C., & Mayland, H. (1982). Mt. St. Helens Ash: Considerations of its fallout on rangelands. Retrieved from http://eprints.nwisrl.ars.usda.gov/1128/1/615.pdf

Stewart, C., Horwell, C., Plumlee, G., Cronin, S., Delmelle, P., Baxter, P., Calkins, J., Damby, D., Morman, S., & Oppenheimer, C. (2013). Protocol for analysis of volcanic ash samples for assessment of hazards from leachable elements. IVHHN Guidelines. Retrieved from http://www.ivhhn.org/index.php?option=com_content&view=article&id=100

Sword-Daniels, V., Wardman, J., Stewart, C., Wilson, T., Johnston, D., & Rossetto, T. (2011). Infrastructure impacts, management and adaptations to eruptions at Volcán Tungurahua, Ecuador, 1999-2010. GNS Science report, Wellington.

Wardman, J. B., Wilson, T. M., Bodger, P. S., Cole, J. W., & Stewart, C. (2012). Potential impacts from tephra fall to electric power systems: a review and mitigation strategies. Bulletin of Volcanology, 74(10), 2221–2241. http://doi.org/10.1007/s00445-012-0664-3

White, J., & Hodgson, J. (1999). New Zealand pasture and crop science. Auckland: Oxford University Press.

Wilson, G., Wilson, T., Cole, J., & Oze, C. (2012). Vulnerability of laptop computers to volcanic ash and gas. Natural Hazards, 63(2), 711–736. http://doi.org/10.1007/s11069-012-0176-7

Wilson, G., Wilson, T. M., Deligne, N. I., & Cole, J. W. (2014). Volcanic hazard impacts to critical infrastructure: A review. Journal of Volcanology and Geothermal Research, 286, 148–182. http://doi.org/10.1016/j.jvolgeores.2014.08.030

Wilson, T., Cole, J., Cronin, S., Stewart, C., & Johnston, D. (2011). Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: lessons for recovery. Natural Hazards, 57(2), 185–212. http://doi.org/10.1007/s11069-010-9604-8

Wilson, T., & Kaye, G. (2007). Agricultural fragility estimates for volcanic ash fall hazards, (December). GNS Science report 2007/37. 52pp.

Wilson, T., Kaye, G., Stewart, C., & Cole, J. (2007). Impacts of the 2006 eruption of Merapi volcano, Indonesia, on agriculture and infrastructure. GNS Science report 2007/07. 71pp.

Wilson, T. M., Stewart, C., Sword-Daniels, V., Leonard, G. S., Johnston, D. M., Cole, J. W., Wardman, J., Wilson, G., & Barnard, S. T. (2012a). Volcanic ash impacts on critical infrastructure. Physics and Chemistry of the Earth, Parts A/B/C, 45-46, 5–23. http://doi.org/10.1016/j.pce.2011.06.006

Wilson, T., Stewart, C., Bickerton, H., Baxter, P., Outes, V., Villarosa, G., & Rovere, E. (2012b). The health and environmental impacts of the June 2011 Puyehue-Cordón Caulle volcanic complex eruption: a report on the findings of a multidisciplinary team. GNS Science report 2012/20, Wellington.

Wilson, T., Stewart, C., & Wardman, J. (2014). Volcanic ashfall preparedness poster series: a collaborative process for reducing the vulnerability of critical infrastructure. Journal of Applied Volcanology, 2, 1–25.

Chapter Six
Forecasting impacts to agriculture from tephra fall

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6.1 Abstract

Developing tools to assess the impact of tephra fall to agriculture is an essential step for informing effective, targeted strategy to reduce the negative consequences. In order to predict the impacts on a system, an understanding of the hazard characteristics and the system's vulnerability characteristics is needed. A useful method of quantifying this vulnerability and predicting impacts after a natural hazard event is through the development and application of fragility functions. Fragility functions give the relationship between a given hazard intensity measure (in this case tephra thickness) and the probability of impacts occurring. Impacts are represented through the use of a damage/disruption state (DPS), which categorises qualitative statements describing the impacts into a numeric scale (from 0 to 4). This study presents a new DPS scheme for pastoral, horticultural, and forestry systems, and a suite of fragility functions showing the probability of each DPS occurring for 14 agricultural sub-sectors. These functions can then be modified to take into account the change in vulnerability that is observed dependent on the time of year (seasonality coefficient). Additionally, for pastoral (including dairying) farming, a coefficient is proposed to take into account the change in vulnerability that occurs when the tephra deposit is high in fluoride (>150 mg/kg). The proposed fragility functions are then used to demonstrate two approaches: 1) in a impact assessment for North Island (New Zealand) agriculture (using hazard surfaces

for a given annual recurrence interval from a probabilistic volcanic hazard model); and 2) in impact assessments of the 1995 and 1996 Ruapehu, and ~1315 Kaharoa eruptions to show the impacts that these eruptions would have on agricultural systems today, and demonstrate their application in a deterministic scenario. These vulnerability tools could be used as part of numerous risk assessments, or during specific eruption scenarios with field-mapped tephra thicknesses. The functions could also be used to develop real-time predictive capacity to aid decision-making.

6.2 Introduction

Assessing the extent and severity of agricultural impacts from tephra hazards and their causal mechanisms is vital when developing risk reduction strategies. It is well documented that tephra can impact a range of agricultural systems and cause both physical and chemical damage (Cook et al. 1981; Cronin et al. 1998; Neild et al. 1998; Wilson et al. 2011). Identification of possible impacts and their spatial distribution allows for impacts to be minimised through targetted mitigation and preparedness strategies. This is an increasing focus of disaster risk reduction (DRR) research (Sparks et al. 2013) and a priority of the UNISDR (United Nations Office for Disaster Risk Reduction) Sendai Framework for Disaster Risk Reduction (UNISDR, 2015). To allow for the identification of impacts, risk assessments are undertaken where the probability of an event’s impacts are calculated using a probabilistic hazard model and vulnerability assessment information (ISDR 2009). This provides information on the distribution and severity of impacts, allowing for targeted DRR work.

Natural hazard risk and impact assessments use hazard and vulnerability information to quantify the probability of different agricultural production changes and/or damage to an exposed region (see Fig. 4.2 for conceptual model). In order to accurately undertake risk assessments, a quantified understanding of the following is required: 1) the hazard intensity metrics (HIM) and spatial constraints (i.e., area affected by tephra fall with respect to thickness); 2) the identification of exposed assets (i.e. spatial location and extent); 3) the vulnerability of exposed assets to volcanic hazards, which connects the hazard and exposure data by determining how a given HIM impacts the exposed assets (i.e., how susceptible assets are to sustaining impacts) (Wilson et al. 2014). Previous studies have identified that tephra fall impacts to agriculture will be governed by the exposed farm characteristics (farm size/type, pre-existing conditions), climate, time of year and existing risk management, in addition to the complex interaction of tephra characteristics (thickness/loading, grainsize, leachates) (Cook et al. 1981; Cronin et al. 1998; Wilson et al. 2011). However, currently this variability in vulnerability is not well incorporated into impact and risk assessment tools. There have been limited attempts to undertake tephra fall risk assessments for agriculture, with previous studies focussed on creating generalised models covering a broad range of agricultural types and systems, where impacts typically increase as tephra thicknesses or loading reach a certain threshold (Jenkins et al. 2014b). Previous agricultural fragility functions have been proposed for different types of agriculture, and also acknowledged the change in vulnerability dependent on the time of year the tephra fall occurs in (i.e., the seasonal vulnerability or seasonality) (Wilson & Kaye 2007). However, previous studies have not provided a quantitative basis for the change in vulnerability due to seasonality or the influence that potential fluoride toxicity in livestock would have on impacts.

This study builds on previous reasearch by creating a new set of vulnerability tools (fragility functions) to be used in agricultural risk assessments (Section 6.3). These refine and progress previous work (notably Wilson & Kaye 2007), incorporate the latest tephra fall impact research, and consider additional sources of vulnerability. These functions incorporate a range of vulnerability information by considering:

- Farm type – vulnerability to tephra fall impacts is highly dependant on the specific farm type (Wilson & Kaye 2007).
- Farm size – smaller farms (<500 ha) can sometimes have less access to machinery and irrigation in a temperate setting, while larger farms are more likely to have these assets.
- Farming intensity – usually closely related to the climatic zone of the affected area. For example a low intensity farm is likely to be in a semi-arid or agriculturally unfavourable region.

- Time of year tephra fall occurred (seasonality) – the timing of the tephra fall is critical in considering the farm activities occurring at the time, e.g., different vulnerabilities associated with different harvest or growth periods.
- Leachable fluoride chemistry – tephra-sourced fluoride has been demonstrated to cause both acute and chronic fluorosis deaths in livestock across various agricultural settings. When considering pastoral agriculture high leachable fluoride (>150 mg/kg) is an additional source of vulnerability (Cronin et al. 2003).

Finally, this study applies the new suite of fragility functions as the vulnerability input for an agricultural tephra fall impact assessment of the North Island of New Zealand, using a probabilistic volcanic hazard model (Hurst & Smith 2010) (Section 6.4). This allows for the identification of farms most at risk of tephra fall impacts, taking into account their likely exposure and vulnerability characteristics. The identification of these high-risk areas could allow for the development of targeting DRR strategies.

6.3 Agricultural fragility function development

6.3.1 Vulnerability assessments

6.3.1.1 Vulnerability assessments

Risk assessments use hazard and vulnerability information to quantify the probability of impacts and/or damage to an exposed region (ISDR, 2009). In order to accurately undertake this assessment, three critical components need to be quantified and well understood: 1) the hazard intensity metrics and spatial constraints (i.e., the characteristics and distribution of the hazardous event); 2) the exposed assets and their properties (such as critical infrastructure components, primary industries, and human life); 3) the vulnerability of the exposed assets to particular hazards (Wilson et al. 2014). Understanding the vulnerability of a specific farm type is vital as this information, along with the HIM, determines the impacts that will occur on the exposed farm (Wilson & Kaye 2007). This means that an accurate understanding of how vulnerable an exposed asset is to impacts from an event is required to forecast the impacts. Quantification of vulnerability is an essential input into robust quantitative risk assessments, however this has been underdeveloped in volcanology (Wilson et al. 2012). Assessing the vulnerability of assets to the impacts of natural hazards can be undertaken using various different methods, ranging from qualitative descriptions through to numerical modelling (Jenkins et al. 2014a).

Vulnerability assessments can be undertaken using a variety of approaches, from simplistic qualitative assessments to fully quantitative fragility functions. For a review of these methods, their limitations, and published examples, see Table 6.1. Currently the most complex vulnerability assessment tools are vulnerability and fragility functions. The development of these functions requires an understanding of the impacts that will occur when a given asset is exposed to a measured hazard intensity metric (Reese & Ramsay 2010). Vulnerability functions aim to show loss of production, function or actual damage with a particular hazard intensity; whereas fragility functions assign a probability of a particular damage state or impact level being reached or exceeded (Tarbotton et al. 2015). Damage states (or impact levels) categorise impacts to assets into a number of defined states, which each have a qualitative description of impacts and often a quantitative measure (such as percentage damage, repair cost) (Blong, 2003b). Both types of functions show a continuous relationship between hazard and impact, rather than discrete threshold associated with damage states. This study will focus on the development of fragility functions, as they incorporate some uncertainty through the use of probabilities. However, these functions are only accurate for the specific asset types that they have been developed for, necessitating the production of numerous functions for different sectors (Rossetto et al. 2014). Fragility functions created for earthquake and tsunami hazards commonly use a lognormal cumulative distribution function to define the fragility curves, and methods such as least squares estimation to derive a mathematical equation for the curves) (Appendix C.1). These methods require a large amount of data to create statistically valid conclusions, which restricts the number of fragility functions available. When less impact data is available simple statistical methods may be more appropriate and expert judgement can be appropriate. The creation of vulnerability or fragility functions is highly dependent on the quality and quantity of impact and hazard information (Rosetto et al. 2013).

Table 6.1: Descriptions, limitations, and examples of different pre- and post-event vulnerability assessment methods, ranging from the simplest to the most complex.

	Description	Limitations	Volcanic hazard application	Tephra fall and agriculture application
Qualitative exposure assessments	These exposure assessments are usually comprised of qualitative statements describing the likely impacts to assets due to the occurrence of a hazard.	These do not identify why different impacts will occur and often treat assets as homogenous in design.	Impacts to critical infrastructure qualitatively described in Wilson et al. (2012) based on previous case studies.	Description of impacts to exposed agriculture have been qualitatively assessed after numerous previous events including: 1980 Mt. St. Helens (Cook et al. 1980); 2006 Merapi (Wilson et al. 2007); 2010 Pacaya (Wardman et al. 2012); and 2011 CC-VC (Wilson et al. 2012).
Qualitative vulnerability assessments	Factors which determine the vulnerability (or resilience) are identified and their relative influence qualitatively or quantitatively expressed.	Assigning the relative influence of different vulnerability characteristics can be subjective.	The identification of infrastructure vulnerability indicators on Vulcano Island, Italy by Galderisi et al. (2012).	Identification of aspects that increase agricultural vulnerability such as climate and access to irrigation after the 1991 Hudson eruption (Wilson et al. 2011).
Damage states	Damage states categorise impacts to assets into a number of defined states, which each have a qualitative description of impacts and often a quantitative measure (such as percentage damage, repair cost).	Qualitative descriptors may not cover the full range of impacts. Some situations may not fit into a singular state. The division of impacts into damage states usually based on expert judgement.	Spence et al. (1996) proposed a damage state scale to classify building damage after the 1991 Pinatubo eruption.	Damage states for agricultural systems were proposed as part of the UN-ISDR Global Assessment Report on Disaster Risk Reduction (Jenkins et al. 2014b), tephra thickness ranges were also assigned to each state based on previous case studies.

	Description	Limitations	Volcanic hazard application	Tephra fall and agriculture application
Impact thresholds	As with damage states, the impacts are categorised into states. Additionally, hazard intensity thresholds are assigned to each state. This allows for damage states to be assigned in a predictive capacity, when hazard intensities are forecasted.	Assumes that hazard intensity will affect all assets uniformily. Does not always take into account the variety in asset design and function which will influence vulnerability.	A 'volcanic building damage scale' with qualitative descriptions and the associated dynamic pressures generated by pyroclastic flows was produced for Vesuvius (Spence et al. 2004). Wilson et al. 2014 proposed an impact state scale for infrastructure sectors with tephra thickness thresholds for each.	
Vulnerability functions	These show the damage, loss of function, or economic losses, as a function of hazard intensity.	Vulnerability and fragility functions require relatively large sets of data, and are only as reliable as the data inputs. They also only use one hazard intensity measure, which may not be the best estimate of impacts in every scenario.	Pomonis et al. (1999) used tephra thickness and Spence et al. (2005) used tephra loading to create vulnerability functions showing the probability of roof collapse.	Wilson and Kaye (2007) proposed a set of vulnerability functions for New Zealand agricultural sectors. These correlated tephra thickness with a damage ratio.
Fragility functions	Fragility functions show the probability of a damage state being reached or exceeded when a particular hazard intensity occurs.		Zuccaro et al. (2008) created functions showing the probability of buildings being within a particular damage state given a particular tephra loading.	This study aims to create fragility functions showing the probability of different agricultural systems falling into a particular damage state with tephra thickness.

6.3.1.2 Previous vulnerability and fragility functions for volcanic hazards

Despite the utility of vulnerability and fragility functions in volcanic risk assessments and subsequent DRR work, there has been less emphasis on developing functions for volcanic hazards compared to earthquake, hurricane and flooding hazards (Wilson et al. 2014). This is in part explained by insurance agencies rarely considering volcanic risk or investing in the development of volcanic risk models until recently (Spence et al. 2009), with the focus on quantitative volcanic risk assessment tools being furthered by the large economic costs caused by the 2010 Eyjafjallajökull eruption (Johnston & Jeunemaitre 2011). Additionally, the complex nature of volcanic hazards, where a range of chemical and physical processes can cause impacts makes the creation of quantitative risk models challenging. Whilst volcanic eruptions are often high consequence events, they occur infrequently and developing resilience to these hazards is often not required in many asset design and building codes.

Despite these challenges, vulnerability and fragility functions have been created for tephra fall, pyroclastic density currents (PDC), and ballistic hazards (Appendix C.1). These have predominantly focussed on the impacts to roofing and the built environment, however increasingly efforts have focussed on critical infrastructure (Kaye 2008; Wardman et al. 2012) and primary industries (Wilson & Kaye 2007). In order to improve volcanic vulnerability and fragility functions continued refinement of functions is needed as new data becomes available. To date, functions have been developed relatively independently and often for particular contexts or case-studies, which reduces their application more generally. While this is appropriate at individual study scale, it has limited the progress of fragility function development progress in the wider volcanic impact and risk community because of the lack of standardised guidelines for the creation of functions, in contrast with seismic hazards as part of the GEM (Global Earthquake Model; Rossetto et al. 2014).

6.3.1.3 Vulnerability and fragility functions for agricultural systems

A range of natural hazards, including geological, biological and meteorological events, can impact agricultural systems (Whitman 2014). Assessing the risk that these hazards pose to agriculture is vital in informing DRR in order to maintain food security and rural community wellbeing (Trujillo et al. 2014). Due to the diverse nature of agricultural systems and the hazards faced, many risk assessments remain primarily qualitative in nature. However, quantitative risk assessments are being developed for many hazards.

A brief review of international studies suggested that natural hazard risk assessments for agriculture (especially weather related hazards) have been undertaken, however the fragility functions are often not publically available (often as they are considered proprietary). Where approaches were documented, a range of methods are used depending on the objective of the risk assessment and available data. Giorgetti et al. (2013) developed fragility functions which considered flood impacts to pasture, crop and livestock. For pasture and crops a vulnerability function was created using a damage ratio (defined by Giorgetti et al. 2013 as the percentage pasture killed) as the dependent value and the duration of inundation (in days) as the independent value. In contrast when considering livestock vulnerability the HIM selected (therefore most likely to influence vulnerability) to show the change in damage ratio was the water depth (m). Livestock were also divided into three types (sheep (unshorn) and lamb; cow, horses, and deer; sheep (shorn), pig, goat and poultry) to show their varying levels of vulnerability to flood hazards.

An attempt to quantify crop vulnerability to drought has been proposed based on an international dataset by Li et al. (2009). This vulnerability assessment relies on the correlation of a Drought Risk Index (the relationship between drought frequency and severity, and production levels and access to irrigation), with yield reduction rate (%) based on previous events. This provides a linear function describing the change in crop production with drought vulnerability. Agricultural assets are very exposed to wildfire as they may be located near likely ignition points, cover large areas, and fire can not easily be mitigated against in an agricultural setting (Vadrevu et al. 2010). Quantitative risk assessments for fire rely on numeric models taking into account the relative likelihood of fires based on the vegetation type and moisture, temperature, humidity, and slope (Hardy 2005). The most adopted quantitative risk assessment tool is called FARSITE, which uses a series of equations to predict fire behaviour and spread (Finney

2004). This model has been used in a number of studies, where in the absence of true vulnerability or fragility functions, total damage has been assumed to occur where the fire happens (Carmel et al. 2009; Chuvieco et al. 2010; Finney 2005).

Forestry is a sector that is particularly at risk of storm events. Qualitative relationships between the age of the forestry, the root structures, the buffering effect of trees on the outer parts of the stand, the aerodynamic roughness of trees, and impacts have been well described (Drouineau et al. 2000). Quantitative functions have been placed on: the threshold wind speed for which trees of a certain age will undergo breakage and overturning (Gardiner & Quine 2000), and a vulnerability function created to show the likelihood of the value of a forestry stand decreasing due to wind damage with increasing age (Birot & Gollier 2001).

6.3.1.4 Volcanic vulnerability and fragility functions for agricultural systems

Creating fragility (or vulnerability) functions for agricultural systems for any natural hazard event presents a unique challenge due to the complexity of the systems that agriculture encompasses. A thorough understanding of the different agricultural characteristics determining vulnerability is needed to undertake any qualitative vulnerability assessment. Agriculture is made up of a range of diverse sectors (such as pastoral, horticulture, and forestry), and each use unique farming methods. Agricultural vulnerability assessments are further complicated by environmental considerations, which can influence the size and intensity of farming in the region, and the pre-existing condition of animals and crops. Additionally, the exposed farms access to assets such as machinery, shelter, and feed stores is also important. These complicating factors necessitate the creation of a number of fragility functions that can be used in various situations. Tephra fall also presents a different set of challenges compared to other natural hazards, as it can cause impacts due to both its physical and chemical nature. The physical properties of the tephra deposit (such as thickness, loading, and grain size), and the environmentally available chemical concentrations both need to be quantified in order to create an accurate risk assessment of the tephra to agricultural systems.

Only one set of vulnerability functions for agriculture and tephra fall hazard are publically available (Wilson & Kaye 2007). These are focussed on the New Zealand environment and do not take into account different tephra compositions or farm intensities. These curves estimate first-order economic losses to farms, separating losses into production and asset-bases. Additionally, there was no consideration of the availability of equipment and assets that enable the application of mitigation techniques, which may substantially minimise losses for farms that can rapidly cultivate and/or irrigate after tephra fall. The addition of recent impact assessment data and the current state of knowledge is needed to refine these.

A slightly more simplistic way of representing vulnerability is the use of damage states and associated tephra thickness thresholds. Damage states use a common scale and have qualitative indicators assigned to each level, allowing for observational data to be placed on a numerical scale (Blong 2003). Widely applicable damage state estimates for agricultural impacts due to tephra fall were developed as part of the Global Assessment Report 2015 (GAR-15) on Disaster Risk Reduction for the United Nations – International Strategy for Disaster Reduction (UN-ISDR) (Jenkins et al. 2014b). Five damage states are presented ranging from no damage (D0) to retirement of the previously productive land due to severe tephra inundation (D5). Tephra thicknesses commonly observed at each damage state were then assigned to each sector, based primarily on expert judgement. Whilst this is a useful pre-EIA tool that can be generally applied to a range of events, Jenkins et al. (2014b) acknowledge it does not take into account the influence that different vulnerability characteristics and more specific farm types would have. This is a limitation which is demonstrated when the Jenkins et al. 2014b and Wilson et al. 2014 damage state schemes were applied to agriculture and infrastructure after the CC-VC event (Chapter 2). This was done both in a predictive capacity by matching the damage states to tephra thicknesses and retrospectively assigning damage states using the observed impacts, and demonstrated that tephra thickness alone was not an accurate predictor of impacts. This finding highlighted the need for a more holistic understanding of both the hazard and vulnerability properties of the exposed system.

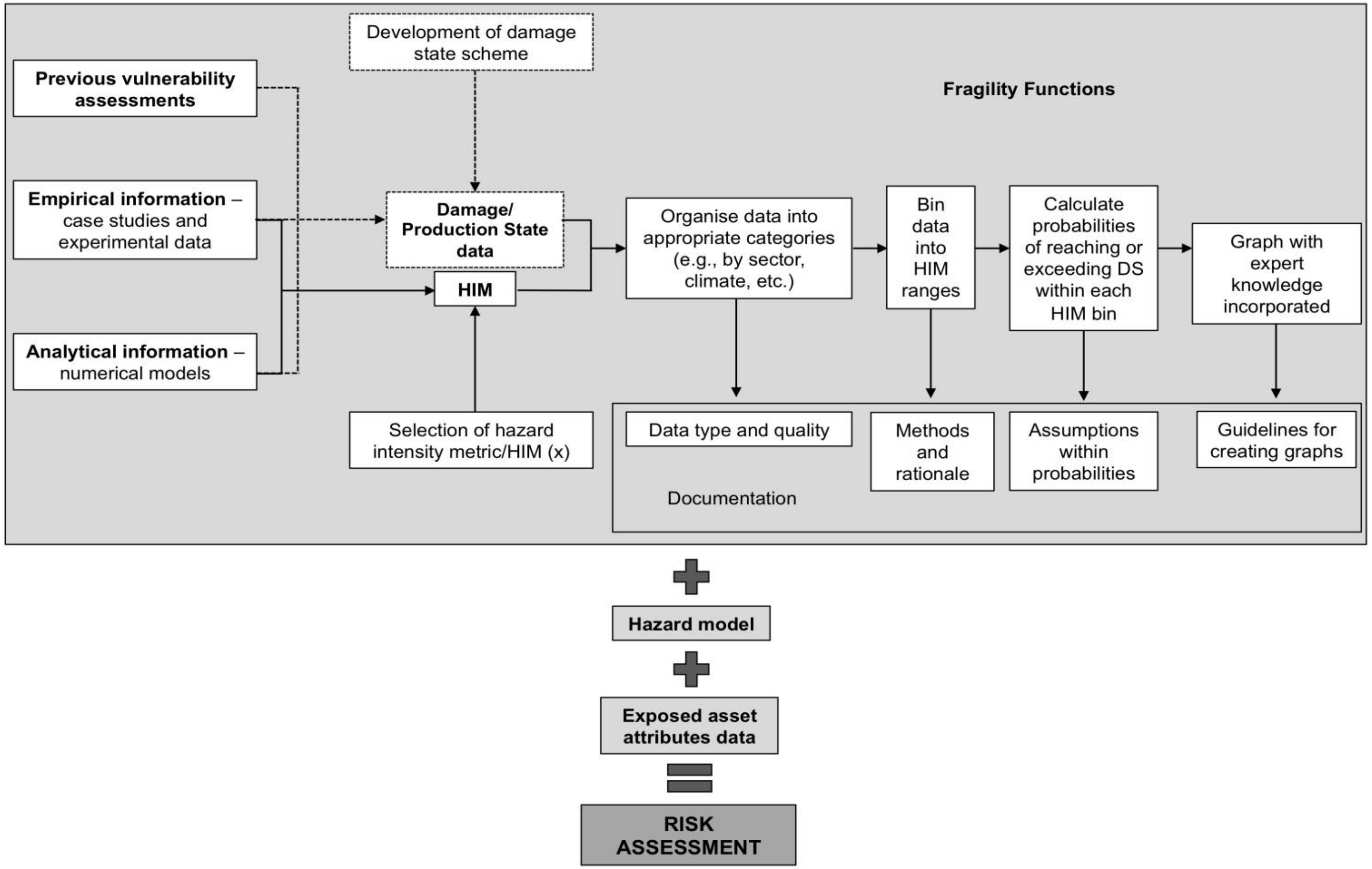


Figure 6.1: Overview of the process of the creation of fragility functions, and the information inputs and components of risk assessments.

6.3.2 Agricultural fragility considerations and methodology

6.3.2.1 Overview

Agricultural fragility functions were created by assessing the probability of a farm exceeding a particular damage state at a given tephra thickness. This was undertaken by the development of damage/disruption state (DPS) schemes for each agricultural sector, which incorporated the production changes that will occur due to the tephra fall, as well as the damage to the assets on the farm (such as vegetation, buildings, and machinery). These DPS were then assigned to empirical impact data points from previous vulnerability studies and case studies. This data was then used along with expert judgement to create a set of 13 agricultural fragility curves for tephra fall. As the functions were developed using an international dataset they are suitable for use in any environment as long as the farm type is included. However, the functions are likely more accurate for temperate environments due to the higher number of case studies and the broader range of agricultural systems affected. However, in the absence of a more region-specific dataset (for arid and tropical environments), these fragility functions can still be applied as part of a risk assessment, however they will have more associated uncertainty which needs to be taken into account. Impact and hazard data sources, as well as expert judgement guidelines are presented in the following methodology sections, with an overview of the process shown in Figure 6.1.

6.3.2.2 Impact data sources

Impact data can be gathered from analytical and empirical sources, and be guided by expert judgement. These three data types are often used in combination to create vulnerability and fragility functions (Rossetto et al. 2014). Large datasets are desirable, as they will cover a wide range of hazard types and intensities and asset properties. This has been a major challenge for the creation of functions for volcanic hazards such as tephra fall, as there are relatively few data sources compared to seismic hazards (Wilson et al. 2014).

Empirical data includes observational studies recorded after an event has occurred, as well as data gathered in an experimental setting. This is the main type of data used to create the set of fragility functions for impacts to agricultural systems due to tephra fall presented here. The most valuable data source for assessing agricultural impacts is post-event impact assessment studies. This is because the unique and complex nature of agricultural systems does not allow for accurate replication of real conditions in experimental conditions. There are a number of factors which will influence agricultural impacts that are challenging to replicate in a laboratory setting, these include: 1) the unpredictable nature of climate; 2) large scale remobilisation; 3) the large scale of farming operations; 4) the actions of farm managers and workers; 5) the wide variation in farm types, and individual methods. This means that the refinement of agricultural fragility functions will likely rely on accurate and robust post-event impact assessments (post-EIA) (Chapter 5).

In the absence of large datasets expert judgement is needed to estimate likely impact levels at different hazard intensities. Primarily this data is used to refine existing functions rather than creating new datasets. Experts need to be familiar with both the hazard and the impacted system (Aspinall 2006).

6.3.2.3 Damage/production state schemes and function sectors

When creating a suite of agricultural fragility functions to quantify vulnerability to tephra fall, the impacts were measured using a range of damage/production states (DPS). In order to create the most accurate fragility functions, agricultural systems were separated into various subsections to take into account the non-uniform nature of vulnerabilities across agriculture. Separate functions for pastoral, horticultural, and forestry were required due to the very different vulnerabilities and exposed assets that comprise the different sectors. Additionally, farms within these sectors were further divided into various subsections based on their products and production processes.

<u>Pastoral</u>

A pastoral DPS scheme was developed specifically for this project in order to allow for the categorisation of impact data. These damage/production states were developed using previous observational studies to assess key indicators of agricultural losses (Chapter 4). These factors included production base losses (e.g. livestock illness and death for pastoral; crop losses for horticultural), external assistance (e.g. supplementary feed, evacuations, cultivation, and/or mitigation assistance), and overall productivity losses. Five main states of damage were identified using the factors described above, and associated production changes, which are presented in Table 6.2. The DPS were designed to be applied at a farm scale in order to address all damage and changes in the productivity of pastoral and horticultural farms. The pastoral farm damage states are separated into two scales, to take into account that the production losses needed to cause a higher DPS are going to be lower in smaller farms as they are more vulnerable to even small productivity changes.

Dairy farming requires greater resourcing, in terms of pasture quality and quantity, access to irrigation, and permanent assets such as milking sheds and distribution equipment. This means that these farms have different sources of vulnerability and require a different DPS scheme. Additionally, dairy farms rely on continued milking during volcanic crises and also need functioning transportation systems to distribute milk products (Matthews et al. 1999). This differs from other types of farming, where given enough clean feed and water, the re-establishment of normal transportation networks is not always required within the initial days after an event. These different vulnerabilities necessitate the development of different sets of fragility functions.

Table 6.2: Damage/production state scheme for small and large pastoral farms.

DPS	Description	PASTORAL FARMING			
		Small farms (<500 ha)		Large farms (>500 ha)	
		Effects on production	***Damages***	**Effects on production**	***Damages***
0	**No disruption**	No production change	*No damage*	No production change	*No damage*
1	**Some disruption**	Supplementary feed required to maintain production (>15% production loss)	*Pasture available insufficient to sustain livestock*	Most losses absorbed within normal boundaries of fluctuating production (<25% production loss), some short-term supplementary feed use	*Some grazing still available, possible abrasion to milking equipment and condensers for dairy farms.*
2	**Moderate disruption**	Large amount of supplementary feed required (15-50% production loss), possible issues with transportation of animals and products due to road transport disruption.	*Most animals unable to graze, animal deaths begin, open water sources contaminated*	Some supplimentary feed required, adverse health effects in exposed animals (~25-50% production loss), possible issues with transportation of animals and products due to road transport disruption.	*Pasture available not enough to sustain livestock*
3	**High disruption**	Entire season production lost, discontinuation of normal farm activities (e.g., mating, shearing, etc.) (>50% production loss)	*Animals unable to graze due to tephra cover, majority of animals dead, in poor condition, or sold, basic soil fertility indicators (N, P, K) negatively affected*	Total reliance on supplimentary feed, widespread animal sales and evacuations (>60% production loss)	*Animals unable to graze due to tephra cover. Possible damage to farm buildings and fences. Abrasion of machinery.*
4	**Total loss of capabilities**	No production possible for at least one year (>70% production loss)	*Total abandonment of farm - often permanent, vegetation dead*	Widespread mitigation and rehabilitation needed in order for production to resume (>70% production loss)	*Very low likelihood of soil recovery in the next 12 months, >50% animal deaths. Difficulties ploughing tephra into soil. Damage to farm buildings likely.*

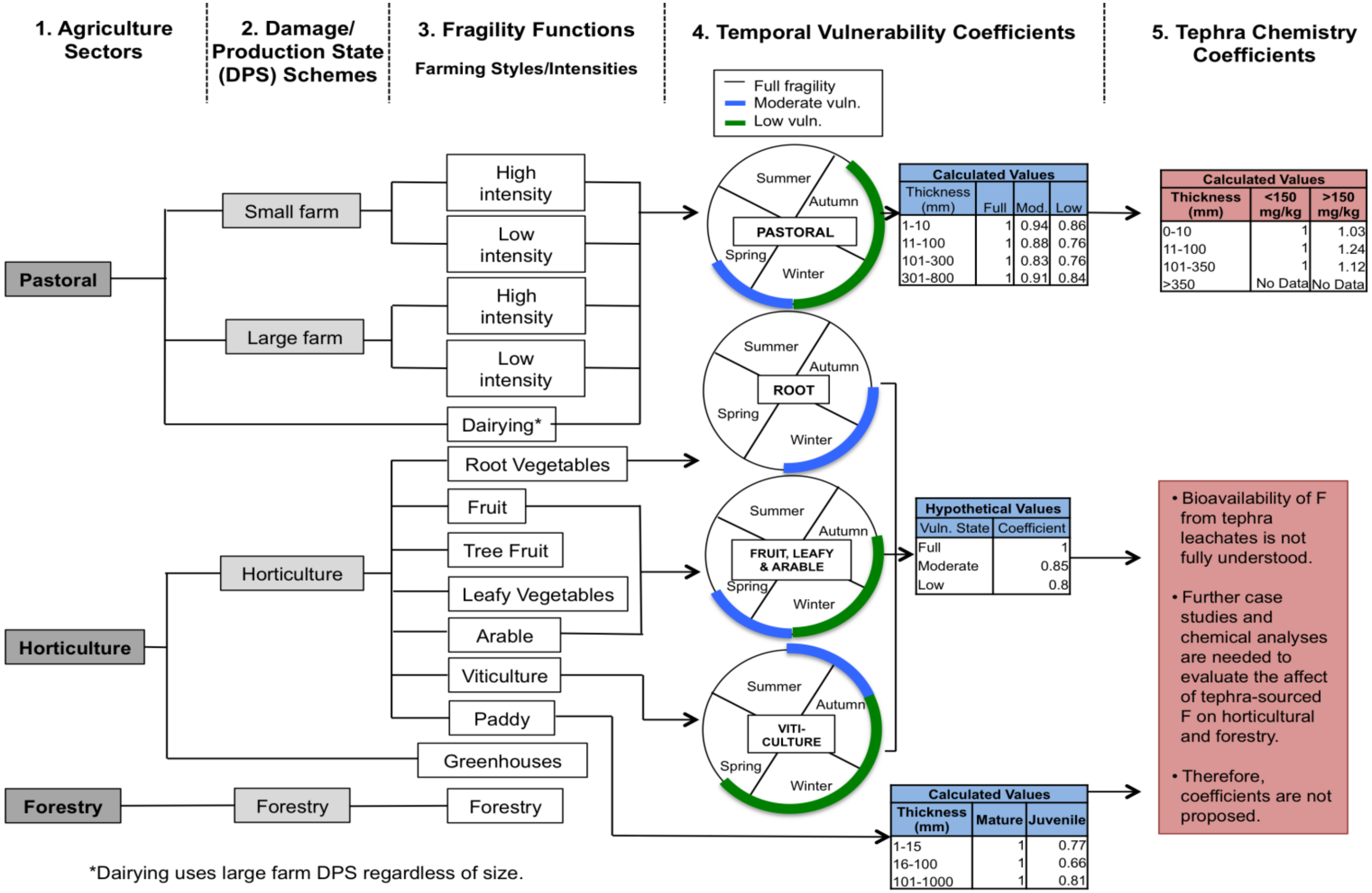


Figure 6.2: Chart showing the separation of agricultural sectors for damage/production state schemes and fragility functions. Also showing which seasonality and leachable fluoride coefficients will be used for each.

Horticulture

A single damage/production state scheme was developed for all of the various types of horticultural farming as the use of production losses and vegetation damages as indicators mean that the DPS scheme can be universally applied. As with pastoral farming, five states were created in order to incorporate damages ranging from no damage to total damage to all vegetation, and various production losses (Table 6.3). Horticultural farms within DPS0 will not suffer any production losses, DPS1 will sustain losses that can be recovered within a season, whereas DPS2, DPS3, DPS4 will sustain up to 20%, 50%, and 75% production losses respectively.

Plant morphology, habit, and the type of fruit or vegetable grown will all influence the resilience of the affected horticultural system. These differences require fragility functions to be developed for the following types of horticulture (classified according to the edible portion of the plant; Arteca 2015):

- Root vegetables – carrots, potatoes, onions, etc.
- Leafy vegetables - lettuce, spinach, cabbage, etc.
- Fruiting vegetables – strawberries, peas, etc.
- Tree crops – apples, citrus, etc.
- Cereals – wheat, oat, barley, etc.
- Viticulture – grape growing
- Paddy farming – rice

Table 6.3: Damage/production state scheme for horticultural farming.

Damage State	**Description**	**HORTICULTURE**	
		Effects on production	***Damages***
0	**No disruption**	No production change	*No damage*
1	**Some disruption**	Slightly lower productivity but recoverable harvest	*<75% vegetation covered*
2	**Moderate disruption**	<25% production loss	*Some plant breakage and damage to crops; possible acid burns and abrasion*
3	**High disruption**	Rinsing/mitigation needed, ~60% production loss	*Most crops sustained some damage*
4	**Total loss of capabilities**	>90% reduction in yield; >1 season to recover,	*All crops damaged in some way. Possible damage to farm buildings*

Forestry

Forestry is the most resilient agricultural sector to tephra fall and required a separate DPS scheme (Table 6.4). This is due to the resilience of mature trees to tephra fall. However, seedlings and young trees are vulnerable to breakage and even burial, which can lead to loss of product (Sands 2005).

Table 6.4: Damage/production state scheme for forestry plantations.

Damage State	Description	FORESTRY	
		Effects on production	***Damages***
0	**No disruption**	No production change	*No damage*
1	**Some disruption**	Minor impact to harvesting. Access roads affected due to poor visabilty	*No damage to trees*
2	**Moderate disruption**	Moderate impacts to tree harvesting; production losses up to 25% for first months	*Some young trees (new plantings) buried. 2-10 year old trees suffer branch breakages. Harvestable trees not damaged.*
3	**High disruption**	Forestry operations temporarily cease due to difficult working environment	*Young plantings often smothered (>50% will not survive). 2-10 year old trees will suffer breakages. Harvestable trees will suffer some breakages.*
4	**Total loss of capabilities**	Production is halted for many years due to difficult conditions	*New plantings all die. 2-10 year old trees suffer severe structural damage. Harvestable trees will survive (with breakages) but will be unable to be harvested due to the very thick deposits.*

6.3.2.4 Hazard intensity metrics (HIM)

Accurate and consistent measurement of the HIM associated with each impact measure is needed to form the independent variable of the fragility curve. The most commonly used HIM when considering tephra fall impacts are physical measures of tephra thickness or loading (Appendix C.1). This is because the majority of impacts to critical infrastructure and primary industries are due to the physical nature of the tephra fall (Wilson et al. 2012). When selecting a HIM it must be: directly related to the intensity of impacts; easily measurable and repeatable in future empirical studies; previously measured in post-event impact assessment trips; and preferably able to be measured by analytical hazard models. This study will use tephra thickness (mm) as it is easily quantifiable in the field and is the HIM most consistently recorded by agricultural impact assessment studies.

6.3.2.5 Fragility functions

Data organisation

Tephra thickness (the HIM) and DPS (the impact measure) data was compiled from a range of sources, including case studies, eyewitness reports, and previous vulnerability studies, and divided into the agricultural sectors described in Section 6.3.3 (Fig. 6.2). The collected data points were then categorised into different vulnerabilities depending on the time of year they occurred. The months of the year were split into vulnerability characteristics based on the farming activities at the time (Table 6.5). Only high vulnerability data points (or events that took place when the affected agriculture was at full vulnerability) were included in the fragility functions. The data points were then arranged in decreasing tephra thickness (mm) and grouped into 'bins' that each have approximately the same number of points (Fig. 6.1). Then for each of the bins the fraction of data points that reach or exceed each DPS is calculated. A corresponding HIM value for each bin is calculated by getting the median tephra thickness value. This method has been employed to create seismic and flooding fragility functions (Porter et al. 2007; Reese & Ramsay 2010; Reese et al. 2011; Tarbotton et al. 2015), and was used throughout this study.

Table 6.5: Generic vulnerability levels for farming types with farm activities and growth stages (FAO 2009).

Pastoral & Dairying

Season		Activity	Vulnerability
Winter	Month 1	Silage often used	Low
	Month 2		Low
	Month 3	Calving	Moderate
Spring	Month 1		Moderate
	Month 2	Lambing	High
	Month 3		High
Summer	Month 1	Spring pasture growth	High
	Month 2		High
	Month 3		High
Autumn	Month 1		High
	Month 2		Low
	Month 3		Low

Fruit, Tree Fruit, Leafy Vegetables & Arable

Season		Activity	Vulnerability
Winter	Month 1	Possible frost protection	Low
	Month 2		Low
	Month 3	Bud burst	Moderate
Spring	Month 1		Moderate
	Month 2	Flowering	High
	Month 3		High
Summer	Month 1	Pruning	High
	Month 2		High
	Month 3	Harvesting	High
Autumn	Month 1		High
	Month 2	Germination	High
	Month 3		Low

Root Vegetables

Season		Activity	Vulnerability
Winter	Month 1	Harvesting	Moderate
	Month 2		Moderate
	Month 3		High
Spring	Month 1		High
	Month 2	Most root vegetables can be sown throughout the year, therefore growth stage and farm activity will vary.	High
	Month 3		High
Summer	Month 1		High
	Month 2		High
	Month 3		High
Autumn	Month 1		High
	Month 2		High
	Month 3	Harvesting	Moderate

Viticulture

Season		Activity	Vulnerability
Winter	Month 1		Low
	Month 2		Low
	Month 3	Winter prune, weed spraying, and maintenance	Low
Spring	Month 1		Low
	Month 2	Insecticide spraying	High
	Month 3		High
Summer	Month 1	Trimming and leaf plucking, irrigation	High
	Month 2		High
	Month 3		Moderate
Autumn	Month 1		Moderate
	Month 2	Harvest	Moderate
	Month 3		Low

Function creation

Once the data has been prepared, the probability of a DPS being reached or exceeded is plotted against the median tephra thickness for each bin. Previous vulnerability and fragility functions have used cumulative lognormal and logarithmic forms, however this study will use a linear form between each bin's data point. This is because the relatively small dataset does not allow for a more complex trend to be identified. This means that for each of the agricultural fragility functions in Section 6.3.3, there are 3-4 discrete linear equations for each DPS, corresponding to the 3-4 bins created. These form the following linear equations:

$$P\,(DPS \geq DPS\chi) = \begin{cases} 0 & HIM = 0 \\ m_1 HIM + c_1 & t_1 \leq HIM < t_2 \\ m_2 HIM + c_2 & t_2 \leq HIM < t_3 \\ m_3 HIM + c_3 & t_3 \leq HIM < t_4 \\ m_4 HIM + c_4 & t_4 \leq HIM < t_5 \end{cases}$$

Where m_1, m_2, m_3, and m_4 are slope constants and c_1, c_2, c_3, and c_4 are the intercepts. t_1, t_2, t_3, t_4, and t_5 are the tephra thicknesses defining each of the thickness bins. P ($DPS \geq DPS\chi$) is the probability of a given damage and productivity state being reached or exceeded.

Due to the small amount of empirical information available for each agricultural category (often less than 15 data points), expert judgement was also used to refine the fragility functions. This was necessary as incomplete datasets can be misleading, particularly at lower DPS (0 and 1) as there is often a bias towards collecting higher severity impact data (Wilson et al. 2014). In order to incorporate expert judgement and compensate for the incomplete dataset, the following instructions were applied to each of the fragility functions:

1. Lines representing the probability of each DPS being reached or exceeded cannot bisect each other.
2. Where the tephra thickness equals zero, there is no impact, therefore no probability of DPS1 being reached or exceeded.
3. The probability of each DPS being reached or exceeded must increase as tephra thickness increases.

4. The probability of a particular DPS being reached or exceeded cannot be zero or one, as it is not possible to know whether an impact will absolutely occur or absolutely not occur.

Coefficients

In order to better account for differences in impacts dependent on the time of year the eruption occurs and the leachable chemistry of the tephra fall deposit, a series of coefficients were calculated. These can be used during times of moderate or low vulnerability or when leachable chemistry is elevated in fluoride, to modify the existing fragility functions.

Prior to fragility functions being created data points were separated into full, moderate, and low vulnerability dependent on the time of year the eruption occurred and the associated farming activities at the time (Table 6.5). Vulnerability levels were assigned based on generic farming activities for each agriculture type throughout the year. These will differ between different climatic zones and ideally the vulnerability level would be determined based on a local farm activity calendar. Empirical data points during times of full vulnerability were used to create the primary fragility functions. For pastoral farming, where there was a larger dataset (>20) additional fragility functions were created for the data points at moderate and low vulnerabilities, and a percentage difference was calculated (Fig. 6.2). The same procedure was followed for paddy farming, where the full vulnerability mature plants were represented in the primary function, then juvenile data points were used to create a low vulnerability coefficient (Fig. 6.2).

The seasonal coefficients proposed for horticultural fragility functions are not calculated values due to the lack of variation in the vulnerabilities of the data points. Therefore, the proposed coefficients were decided based on expert judgment and consideration of previously proposed seasonal vulnerability differences (Wilson & Kaye, 2007).

The same procedure used to create seasonal coefficients was also used to create a coefficient to represent the increase in vulnerability for pastoral and dairy systems caused by tephra with high soluble fluoride concentrations (>150 mg/kg) (Fig. 6.2). Tephra falls with high soluble fluoride contents have lead to livestock developing fluorosis, which leads to dental lesions, lameness, and gastrointestinal distress (Araya et al. 1990; Flueck 2013). This can lead to a substantial increase in production losses and therefore DPS (Rubin et al. 1994), and needs to be taken into account when using fragility functions for impact forecasting. Whilst the individual soluble chemistry of the deposit and the receiving environment will strongly influence the leachable fluoride concentrations, there is a link between thicker tephra deposits and an increased incidence of fluorosis when considering a singular farm type and event. This means that the existing fragility functions (which rely on tephra thickness as the independent variable) can be modified to incorporate the change in vulnerability with increased leachable fluoride concentrations. However, the effect of soluble fluoride from tephra fall on vegetation is not fully understood (Weinstein & Davidson 2004). Therefore, there is no evidence on which to base any proposed coefficient when considering horticultural and forestry systems. As a consequence there is no fluoride coefficient suggested for these farm types. However, it is important that as part of any risk assessment leachable fluoride is evaluated and its potential hazard taken into account.

6.3.3 Proposed fragility functions

The following section presents each of the fragility functions and shows the number of data points compiled to create each one. The HIM used for all of the functions is tephra thickness (mm), and the impact metric is the DPS from the sectors corresponding DPS scheme (Section 6.3.2.3). The assumptions, uncertainties, and knowledge gaps associated with each function will be discussed.

6.3.3.1 Pastoral

Tephra fall can adversely impact soil, vegetation and animal health (Section 1.2). These impacts can be influenced be a range of vulnerability characteristics that also need to be taken into account when understanding impacts and evaluating mitigative methods (Table 6.6). Impacts and vulnerability characteristics were identified using previous case studies (from other authors as well as in Chapters 3, 4, and 5). These are reviewed and outlined in Table 4.5. The pastoral fragility functions presented here, take into account the following factors that can influence vulnerability characteristics:

1. Seasonality – Through the use of a seasonal vulnerability coefficient. Generic seasonal vulnerability levels are proposed in Table 6.5, however, where possible these should be assigned based on the farming activities in the specific area being assessed.
2. Leachable fluoride – Incorporated by applying a coefficient.
3. The size of the farm – This can influence access to machinery, irrigation, and shelter as smaller farms are less likely to have these.
4. The intensity of farming – This influences animal and vegetation condition, and possibly remobilisation potential. As higher intensity farming takes place in more agriculturally favourable conditions where animal and vegetation conditions are likely to be better, and tephra is more likely to be incorporated into the soil (preventing prolonged wind remobilisation) due to moderate levels of rainfall.

Table 6.6: Tephra fall impacts and vulnerability influences for pastoral farm systems.

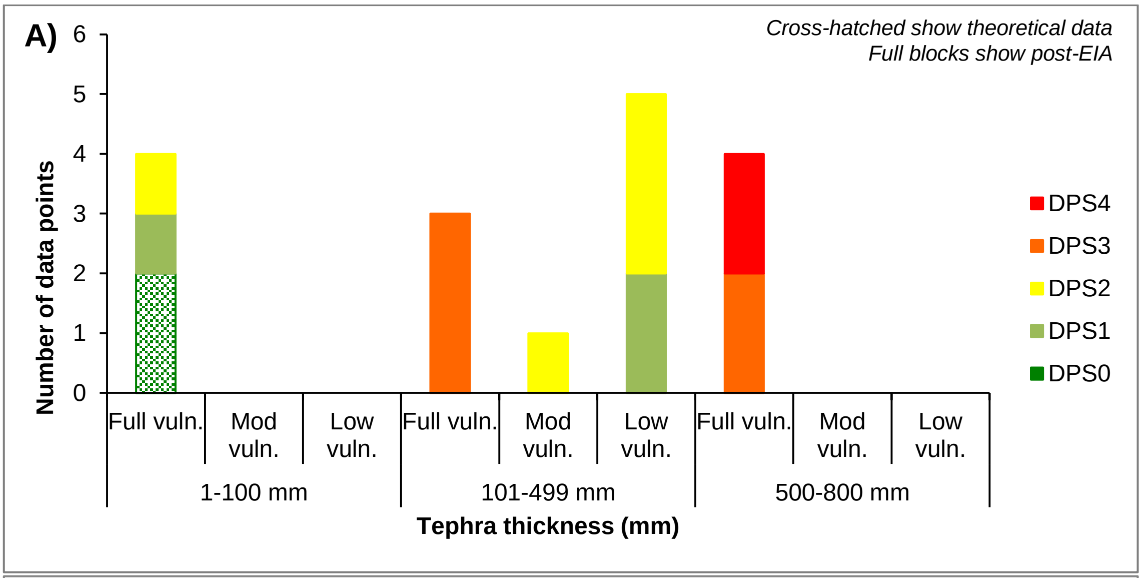
Components	Possible impacts	Vulnerability influences
Soil	Burial Cementation Fertility changes	Soil buffering capacity Irrigation available Access to cultivation machinery Water retaining capacity
Vegetation	Burial Breakage Vegetation coated Lack of water Acid burns Uptake of elements Root damage	Seasonality Vegetation type & requirements Vegetation condition Plant morphology Vegetation condition Strength Leaf texture
Animal Health	Starvation Dehydration Suffocation Tooth abrasion Fluorosis Eye/skin irritation	Animal condition Animal type Feed stores available Shelter access Seasonality Water and feed source type

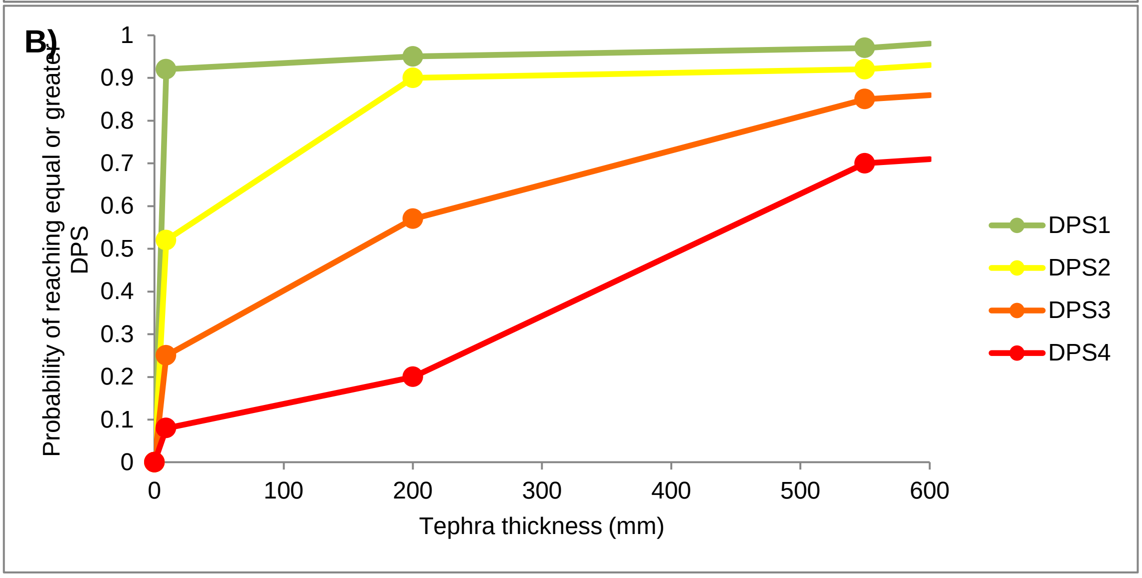
These factors were chosen based on previous case studies (shown in Tables 4.5 and 6.6), but were also selected based on available quantitative information. For example, quantifying and categorising a large dataset of farms that had access to cultivation machinery and irrigation after past case studies is challenging, whereas accessing data on farm size, seasonality, and the leachable chemistry of a tephra deposit is more straight-forward.

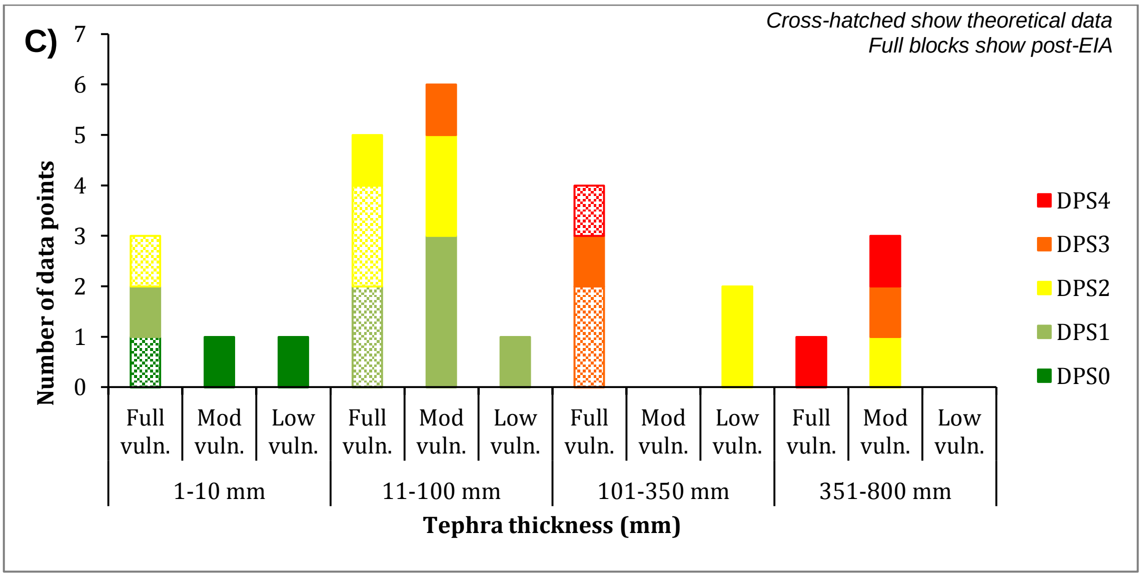
<u>Sheep, beef cattle, and deer farming</u>

Pastoral farming is reliant on non-contaminated pasture suitable for grazing livestock. Initially farmers can rely on supplemental feed to maintain animal condition, however, as feed stocks dwindle or if multiple tephra fall events occur farmers cannot return to intensive feeding for weight gain. Previous studies have divided beef cattle functions, from sheep and deer farming as cattle do not graze as close to the soil (Wilson & Kaye, 2007). Therefore it assumed that cattle would be more resilient as they will ingest less tephra. However, this study has not separated cattle, as there is an insufficient number of data points to interpolate another set of functions. Additionally, many farms in the studies used to form the functions had a mixture of livestock types grazing.

A total of 17 data points (15 case studies, 2 previous vulnerability studies) were used to create the function for small (<500 ha), high intensity pastoral farms, and 28 points (25 case studies, 3 previous vulnerability studies) for large (>500 ha), high intensity farms (Fig. 6.3 a & c). A limitation within both datasets is that DPS4 is likely to be under represented due to farmers often abandoning land or issues with sensitivity when selecting case studies during post-event impact assessment. Conversely, it is likely that DPS3 is somewhat over represented, due to bias towards farms with more significant impacts in post-event impact assessment. These issues were addressed as part of the expert modification of functions.


A)
Cross-hatched show theoretical data
Full blocks show post-EIA
Number of data points
6
5
4
3
2
1
0
Full vuln.
Mod vuln.
Low vuln.
1-100 mm
101-499 mm
500-800 mm
Tephra thickness (mm)
DPS4
DPS3
DPS2
DPS1
DPS0


B)
Probability of reaching equal or greater DPS
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
Tephra thickness (mm)
DPS1
DPS2
DPS3
DPS4


C)
Cross-hatched show theoretical data
Full blocks show post-EIA
Number of data points
7
6
5
4
3
2
1
0
Full vuln.
Mod vuln.
Low vuln.
1-10 mm
11-100 mm
101-350 mm
351-800 mm
Tephra thickness (mm)
DPS4
DPS3
DPS2
DPS1
DPS0

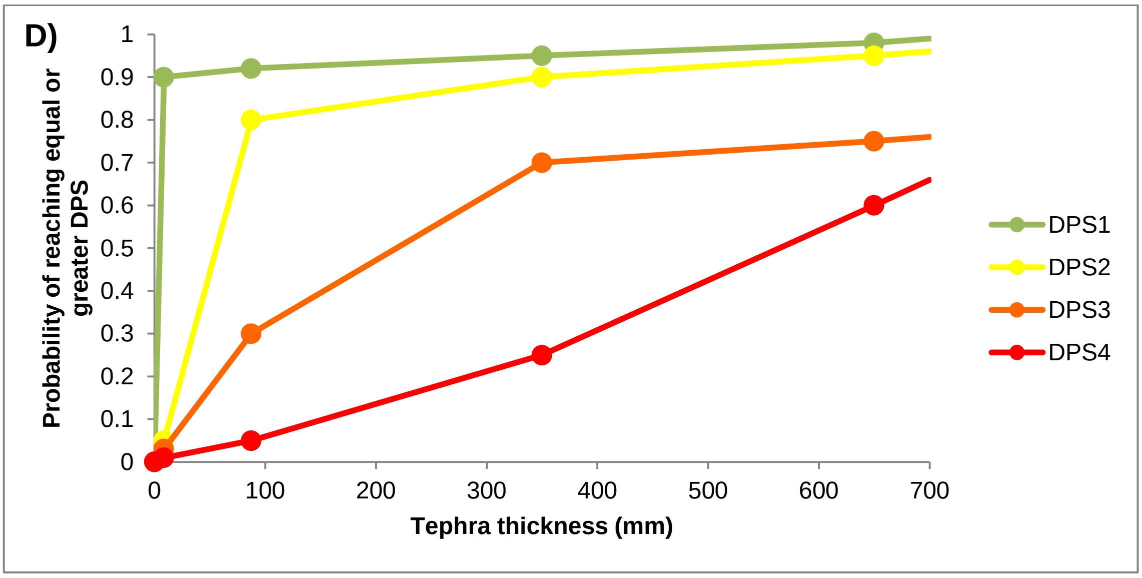
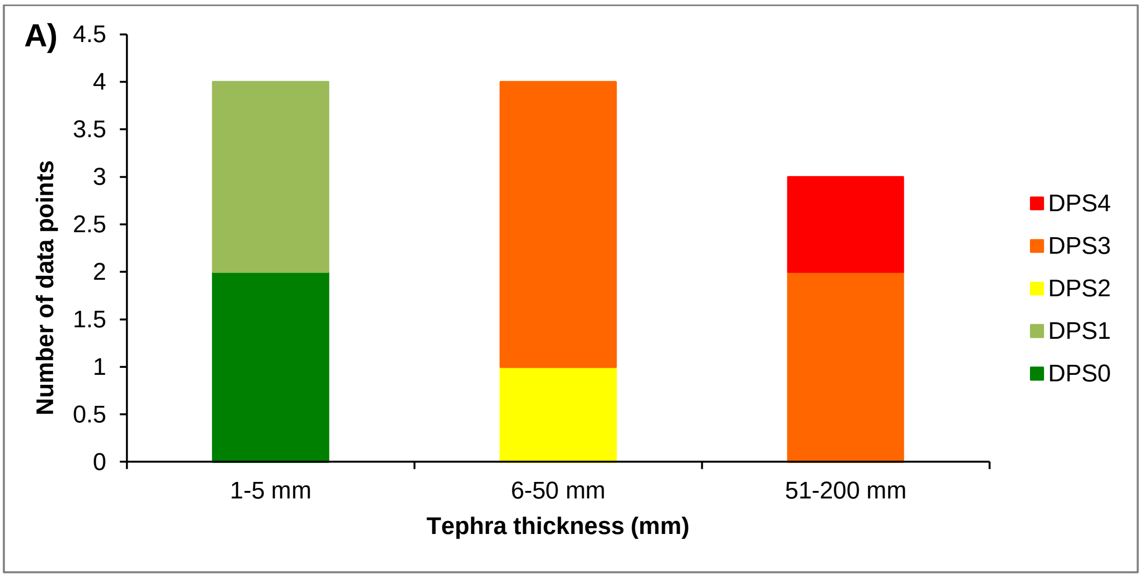
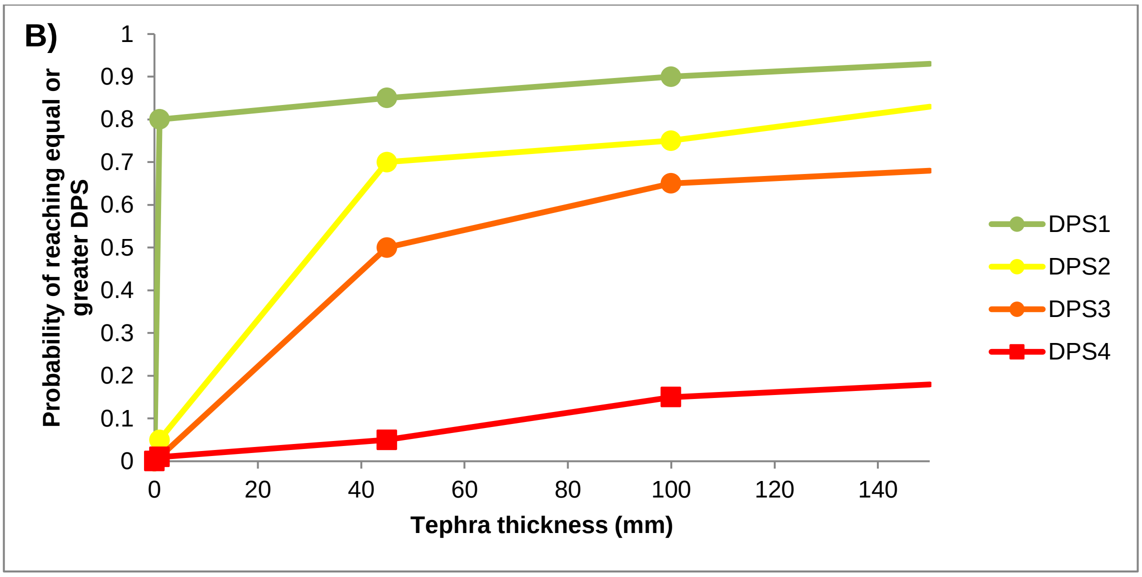


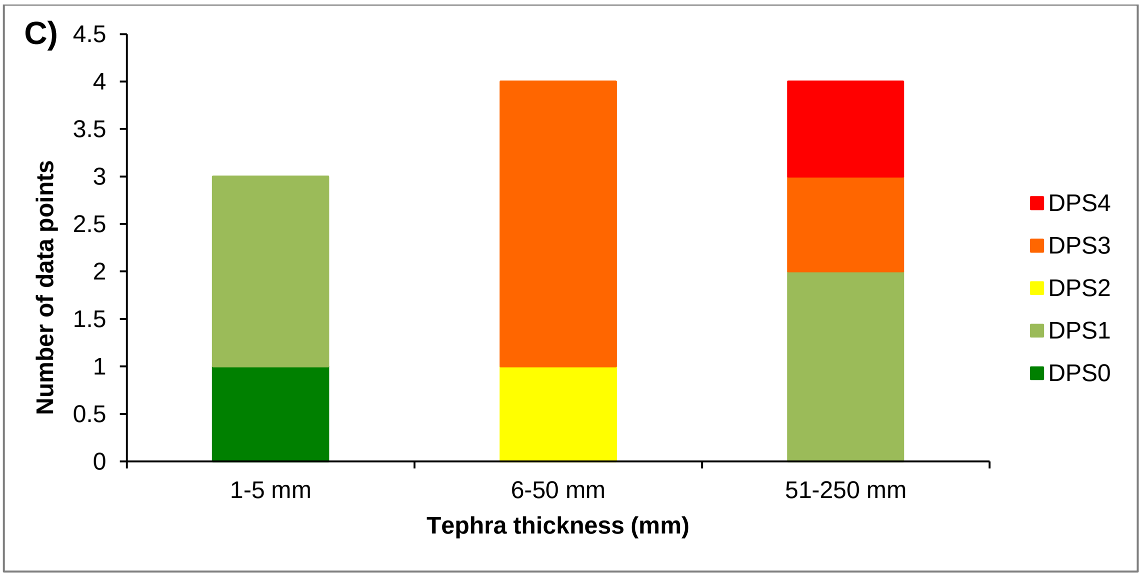
Figure 6.3: High intensity pastoral farming fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin for small farms (<500 ha); B) fragility functions for small, high intensity farms; C) histogram showing the number of DPS data points available for each tephra thickness bin for large farms (>500 ha); D) fragility functions for large, high intensity farms.

Functions for low intensity, pastoral farming were created using 12 data points from previous case studies for large farms and 11 points for small farms (Fig. 6.4 a & c). A major issue with the dataset for low intensity farming is that the impacts at greater than 100 mm tephra thickness are poorly constrained. This is because the current dataset includes few points from higher tephra thicknesses, and none from greater than 200 mm.

Fragility functions for high intensity, pastoral farming (≥3 stock units per hectare; Fig. 6.3b & d) show that they are less vulnerable to tephra fall impacts than low intensity, pastoral farms (<3 units/ha; Fig. 6.4 b & d). This is likely due to greater access to feed supplies and machinery for tephra removal or cultivation. High intensity farms are also less likely to occur in environmental regions prone to remobilisation. For example, many low intensity farms are located in semi-arid or arid regions where prolonged wind remobilisation of the tephra deposit often occurs increasing the severity of impacts.


A)
Number of data points
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
1-5 mm
6-50 mm
51-200 mm
Tephra thickness (mm)
DPS4
DPS3
DPS2
DPS1
DPS0


B)
Probability of reaching equal or greater DPS
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
Tephra thickness (mm)
DPS1
DPS2
DPS3
DPS4


C)
Number of data points
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
1-5 mm
6-50 mm
51-250 mm
Tephra thickness (mm)
DPS4
DPS3
DPS2
DPS1
DPS0

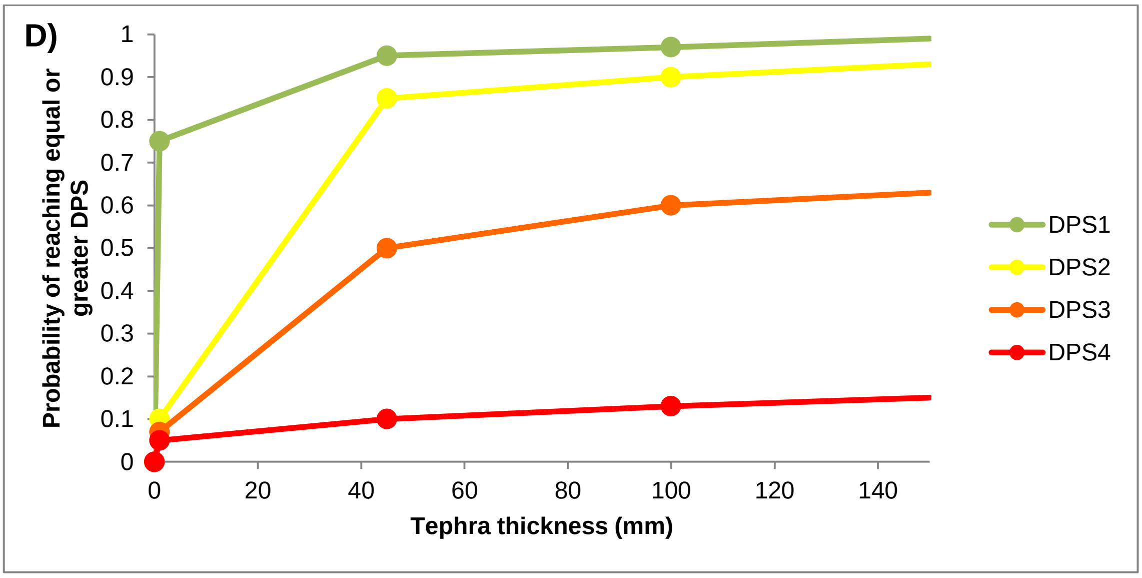


Figure 6.4: Low intensity pastoral farming fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin for small farms (<500 ha); B) fragility functions for small, low intensity farms; C) histogram showing the number of DPS data points available for each tephra thickness bin for large farms (>500 ha); D) fragility functions for large, low intensity farms.

<u>Dairying</u>

Dairying is considered more vulnerable to tephra fall than the other types of pastoral farming (Wilson & Cole 2007; Wilson & Kaye 2007). This is due to the high-energy inputs required for the production of milk, and the dependency on electrical supplies for milking machinery and roading networks for transportation of milk products (Wilson & Cole 2007). After tephra fall farmers are often forced to reduce or discontinue milking, due to a shortage of uncontaminated feed, electricity outages and/or transportation issues. This can lead to cows drying off. Milking cannot be resumed after cows have dried off until the following breeding season (McDonald et al. 2011), leading to up to a year of lost production.

Fragility functions for dairy farming were created using 13 data points (7 case studies, 6 previous vulnerability studies) (Fig. 6.5 a). The dataset was limited compared to the other pastoral categories due to both its smaller size and its greater reliance on previous theoretical vulnerability studies, rather than previous empirical and case study data. The fragility function for dairying demonstrates its greater vulnerability to tephra fall impacts compared to other types of pastoral farming (Fig. 6.5 b).

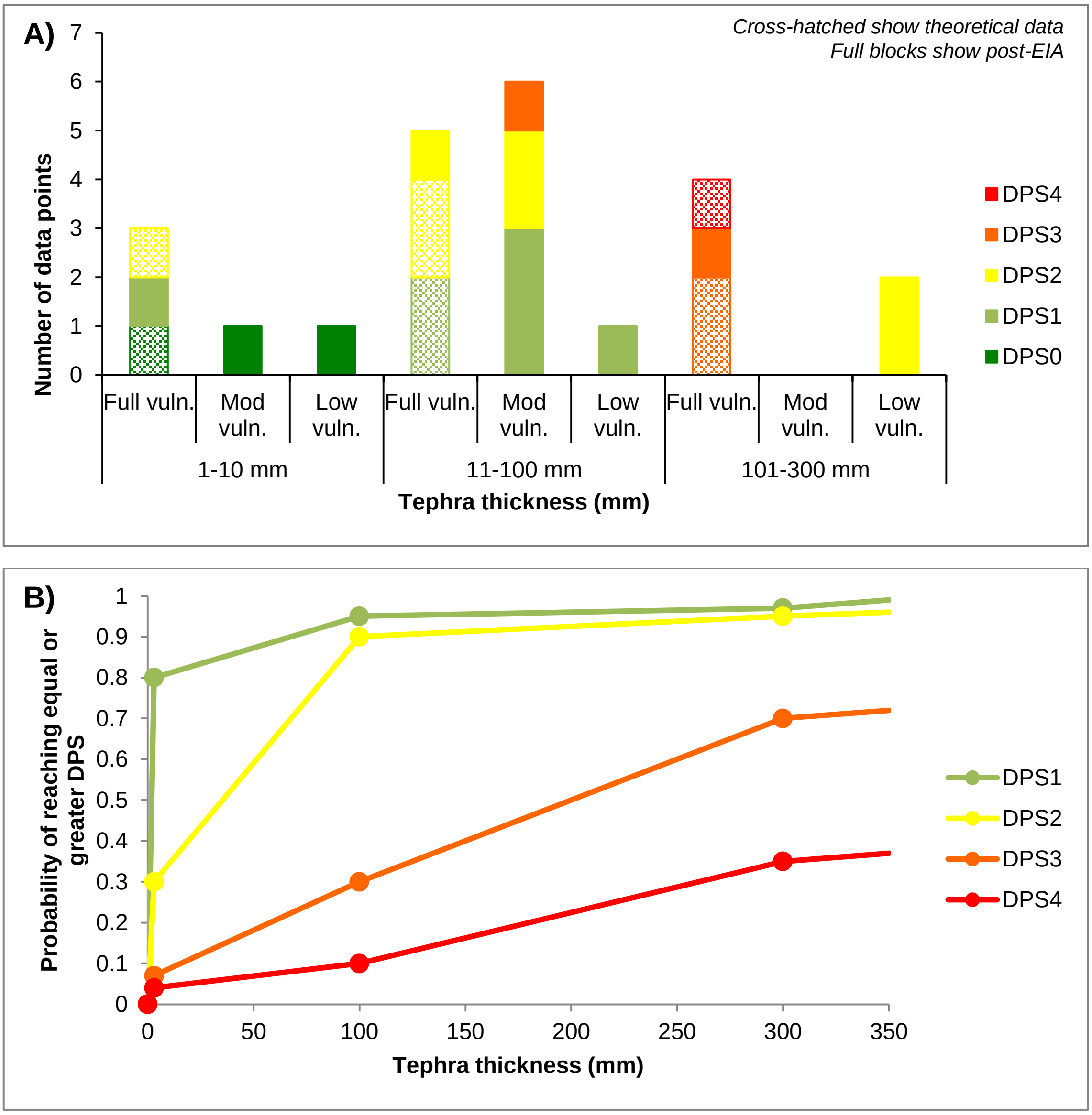
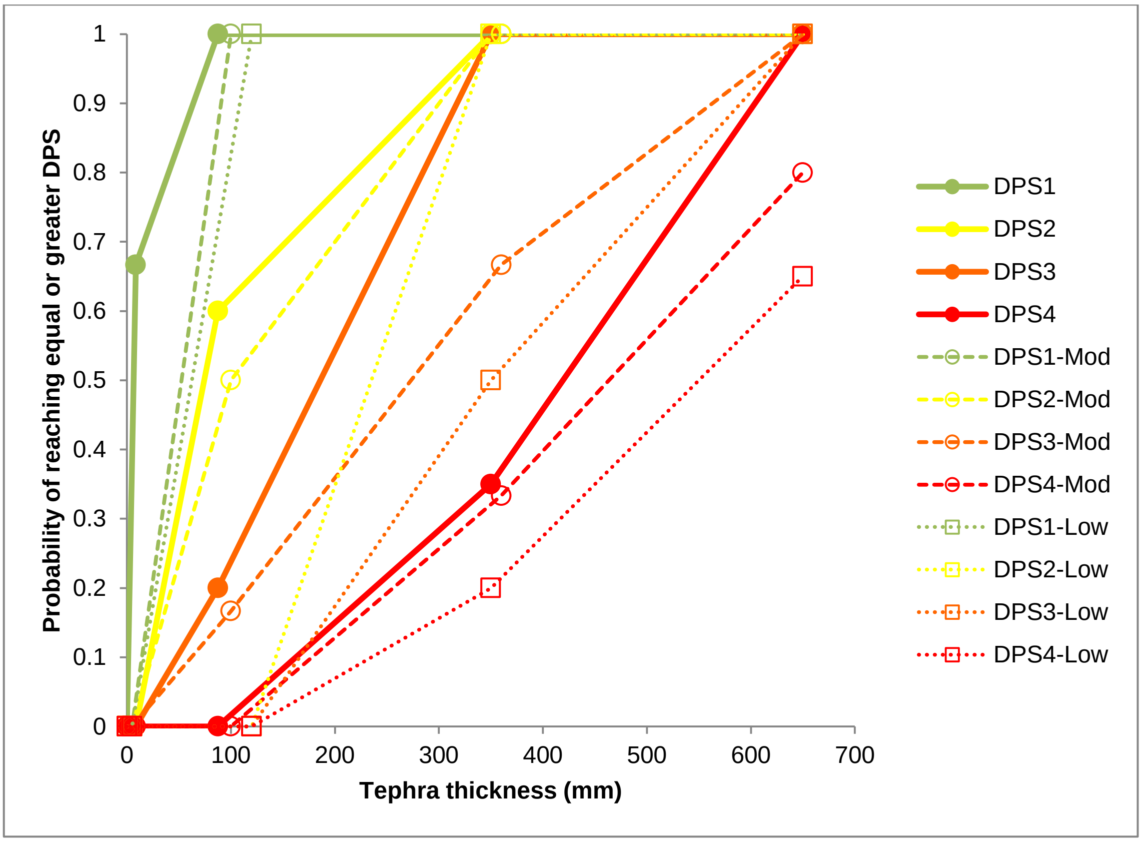


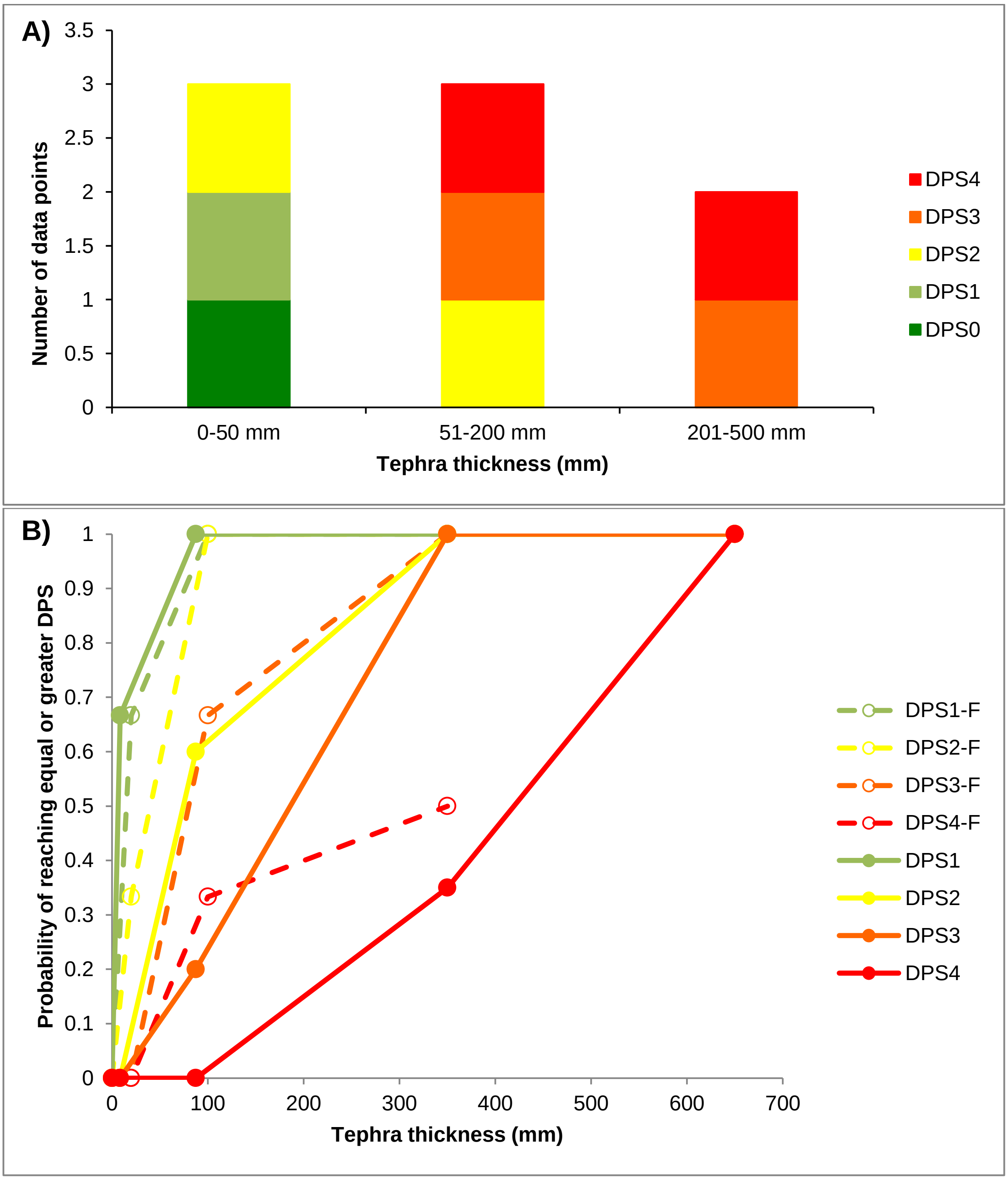
Figure 6.5: Dairy farming fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin for dairy farms; B) fragility functions for dairy farms.

In order to calculate the seasonal and leachable fluoride coefficients (Section 6.3.2.5) the percentage difference between the linear segments was calculated using only the raw data with no expert judgment. When considering full, moderate, and low seasonal vulnerability a series of coefficients for each thickness bin was calculated (Fig. 6.6). These were also calculated for farms with elevated leachable fluoride levels (>150 mg/kg) using functions formed from nine data points from previous post-event impact assessments with high leachable fluoride (Fig. 6.7 a & b). Whilst these were calculated using the large, high intensity pastoral farm dataset, due to the large number of data points, it is likely that the relative difference in vulnerability would be the same for pastoral farms of different types, sizes and intensities.



	Calculated Values		
Thickness (mm)	**Full**	**Mod**	**Low**
1-10	1	0.94	0.86
11-100	1	0.88	0.76
101-300	1	0.83	0.76
301-800	1	0.91	0.84

Figure 6.6: Fragility functions for large, high intensity pastoral farms at full seasonal vulnerability, moderate seasonal vulnerability, and low seasonal vulnerability. This allowed the table of coefficients to be created.



	Calculated Values	
Thickness (mm)	**<150 mg/kg F**	**>150 mg/kg F**
1-10	1	1.03
11-100	1	1.24
101-350	1	1.12
>350	1	No data

Figure 6.7: Calculation of a coefficient to account for the increased vulnerability cause by tephra fall with high leachable fluoride (>150 mg/kg). A) histogram showing the number of data points available for high leachable fluoride tephra fall events; B) fragility functions for high leachable fluoride events compared to functions for large, high intensity pastoral farming.

6.3.3.2 Horticultural

The vulnerability of horticultural systems to tephra fall is highly dependent on the type of crop, its morphology, growth cycle, and the desired product. As with pastoral farming tephra impacts to soil and vegetation health will drive production losses. The horticultural fragility functions here assume the tephra fall occurs at a time of full vulnerability when damage and production losses will be at the maximum. Functions take into account sources of vulnerability through the separation of horticultural crops based on their growth habit and product and the use of a seasonal vulnerability coefficient. Due to the smaller number of data points and an incomplete knowledge of all crop types precise seasonal vulnerability changes, the seasonal coefficient proposed for horticultural crops are hypothetical rather than calculated (as it was for pasture). Additionally, horticulture is highly sensitive to seasonal changes due to the diversity of crop types and industries it is comprised of, and the range of climate, soil types, and available 'improvement' assets (such as cultivation and irrigation machinery). This means that the seasonal level of vulnerability needs to be determined for each individual region and horticulture type.

<u>Root vegetables</u>

Root vegetables are less vulnerable to tephra fall impacts compared to other horticulture where the product is more environmentally exposed. This is because the edible portion of the plant is relatively protected. However, tephra fall can still impact the vegetation above ground, as well as creating a barrier between normal air and water exchange between the environment and the soil.

Fragility functions were created using 13 data points, primarily from the 2006 Merapi (Wilson et al. 2007), 1995 Ruapehu (Wilson & Kaye 2007), and 2008 Chaitén eruptions (T. M. Wilson, unpub. field notes, 2009). The data set did not contain many points with moderate seasonal vulnerability and did still rely on some previous theoretical vulnerability studies (Fig. 6.8 a). Root vegetables showed a relatively low probability of reaching DPS4 even within the highest thickness bin (100-500 mm), compared to other horticulture (Fig. 6.8 b). A limitation of the current data set is that there was little information on the specific cause of elevated DPS (such as chemical or physical vegetation damage, issues with soil fertility, dehydration, etc.). There was also only minimal information on exact root vegetable type and farm practice.

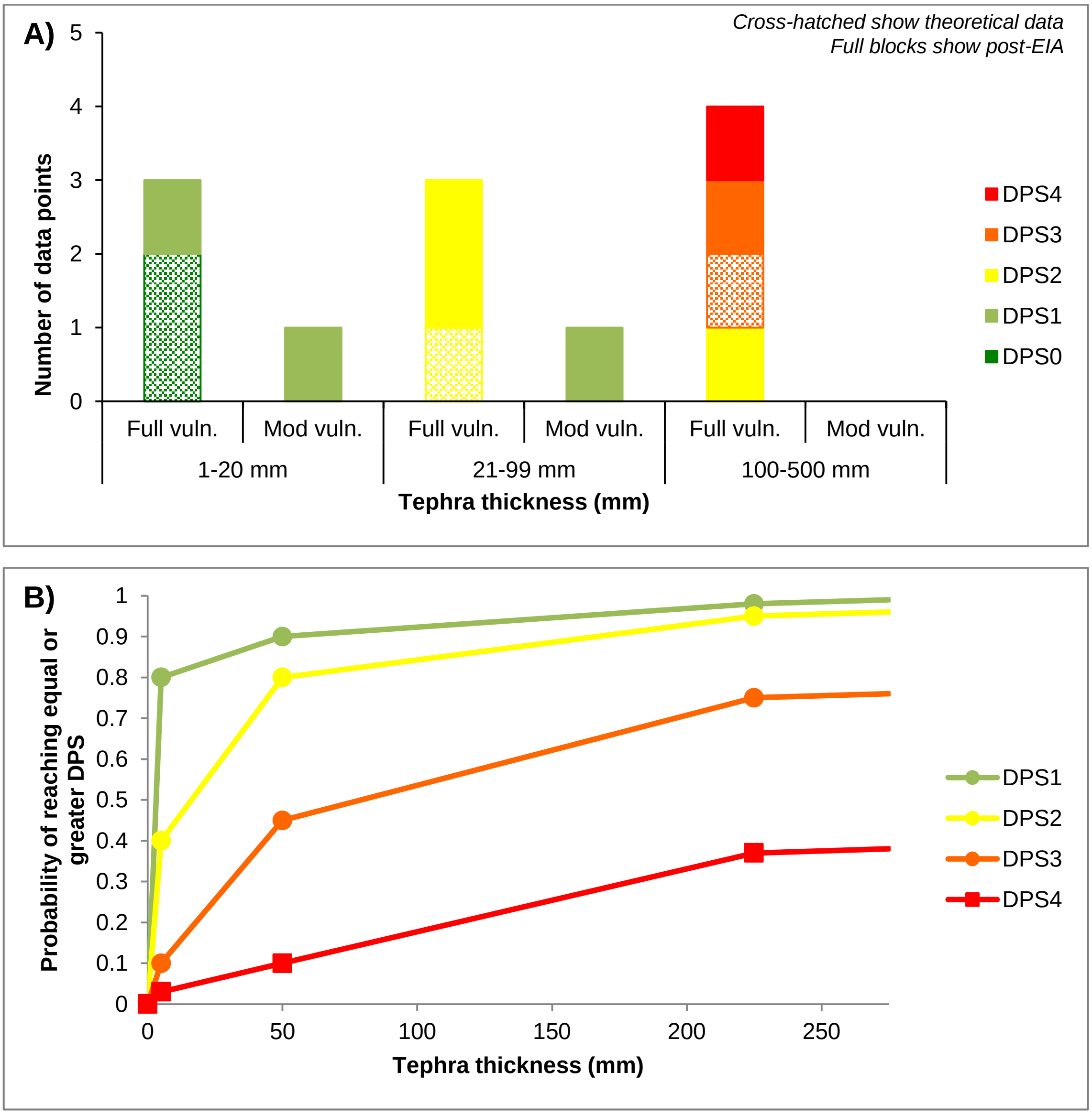
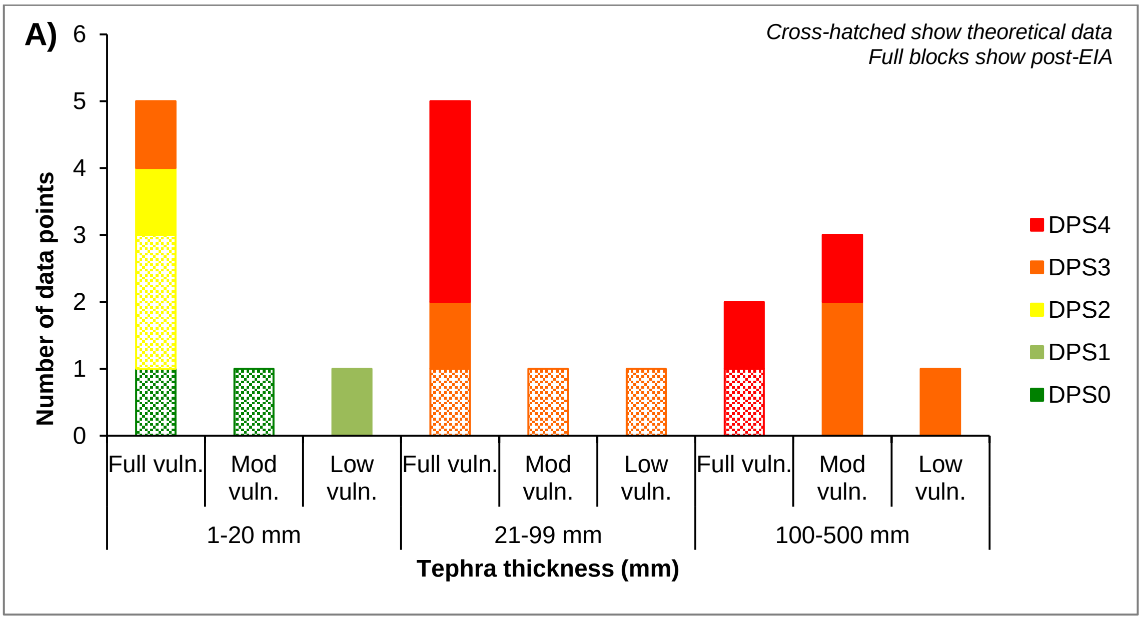


Figure 6.8: Root vegetables fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin; B) fragility functions for root vegetables.

Leafy vegetables

Leafy vegetables are plants were the leafy section is the edible product. These plants are very vulnerable to tephra as they often have a prostrate morphology and large leaf structures that accumulate tephra.

Functions were formed using 20 data points, with some reliance on previous vulnerability studies as well as case studies (Fig. 6.9 a). A limitation of the data set is the small number of DPS0 and DPS1 points. This is likely due to the high vulnerability of leafy vegetables, where only thin tephra deposits are required to cause DPS greater than 1. Future studies of the impacts to leafy vegetables after thin tephra deposits (≤5 mm) need to be incorporated and used to refine the lower DPS thresholds. The data points with full seasonal vulnerability did not include any case studies covering the thickness range between 100 and 400 mm. This gap in the data accounts for the wide spacing between data points (at 22.5 mm and 450 mm), where interpolation is relied upon to provide a function (Fig. 6.9 a). The increased exposure to tephra fall compared to root vegetables is clearly demonstrated by the higher vulnerabilities, where the probability of reaching or exceeding DPS4 is over 50% at ~23 mm (Fig. 6.9 b). This is significantly higher than the vulnerability level of root vegetables (Fig. 6.8 b).



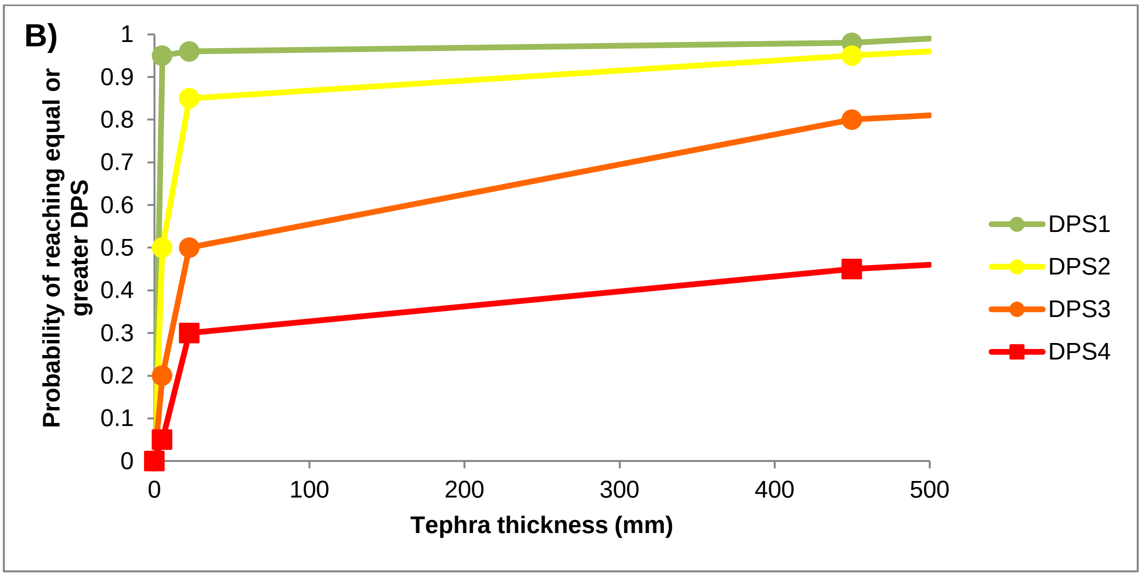


Figure 6.9: Leafy vegetables fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin; B) fragility functions for leafy vegetables.

<u>Fruiting vegetables</u>

Fruit horticulture is likely to be impacted by tephra fall burial and the abrasion of the fruit product. Unlike with root vegetables the edible portion of the plant is exposed to the tephra fall. However, it is likely that the more erect growth habit could make fruiting vegetables more resilient to tephra fall compared to leafy vegetables (which are often prostrate).

Fourteen data points were used to create the fragility functions proposed, with numerous points coming from the 2006 Merapi case study (Wilson et al. 2007). Data gaps include infrequent points between 100 and 300 mm tephra thickness, sparse information about specific differences in impacts between fruit types, and few points at DPS2 (Fig. 6.10 a). Fruit horticulture (Fig. 6.10 b) appears to be less vulnerable to tephra fall impacts than leafy vegetables (Fig. 6.9 b), but more vulnerable than root vegetables (Fig. 6.8 b). This is due to the edible portion of the plant being more exposed to tephra fall than root vegetables, but less exposed than leafy vegetables.

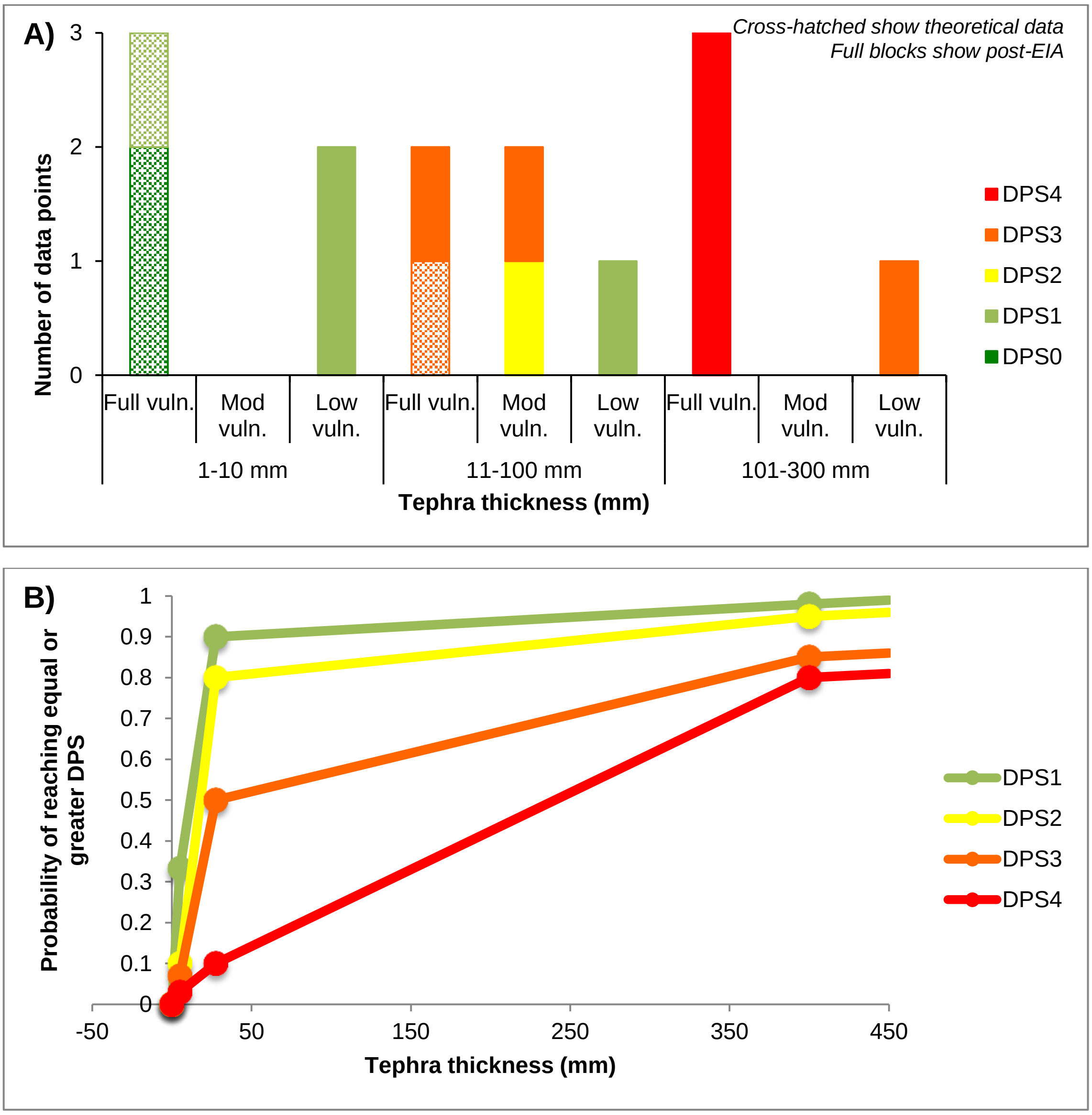


Figure 6.10: Fruiting vegetables fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin; B) fragility functions for fruiting vegetables.

<u>Tree fruits</u>

Tree crops also have products that will be exposed to tephra. However, their growth on tree structures leaves them less vulnerable to tephra. The main damage to crops is usually the pitting and abrasion of the fruit skin due to tephra fall contamination, and breaking of branches and issues with harvesting machinery at higher thicknesses (Neild et al. 1998).

As with fruiting vegetables the main case study providing relevant data points is the 2006 Merapi tephra fall event (Wilson et al. 2007). Data was limited as there was not a wide range of available case studies, and few points at DPS4 (Fig. 6.11 a). Tree fruits were found to be much more resilient to tephra fall compared to other types of horticulture (Fig. 6.11 b). This could be why there is a lack of data at DPS4; due to the relative resilience tephra thicknesses need to be extremely high (usually >300 mm) to begin to cause tree fruits to fall into DPS4.

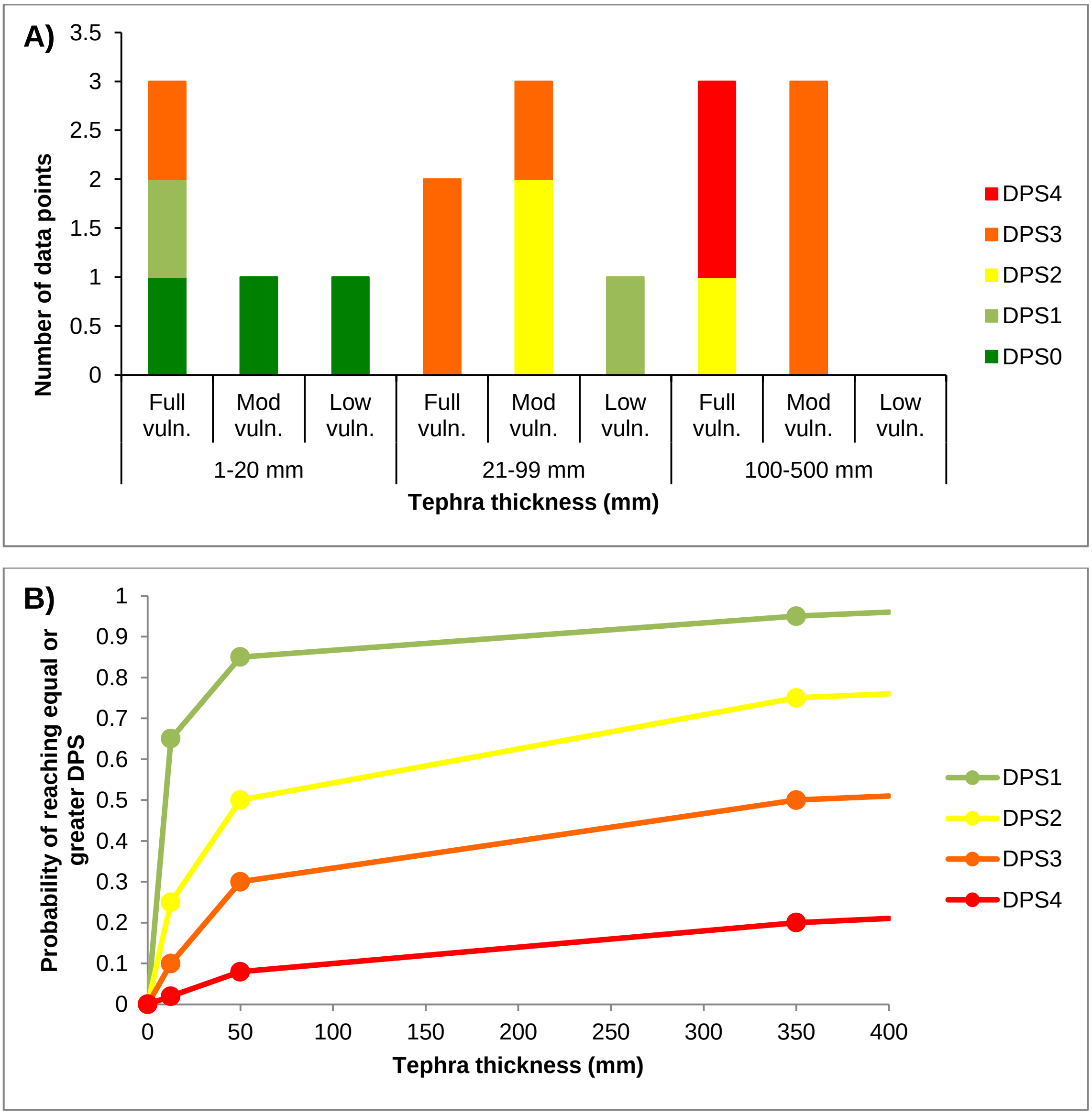
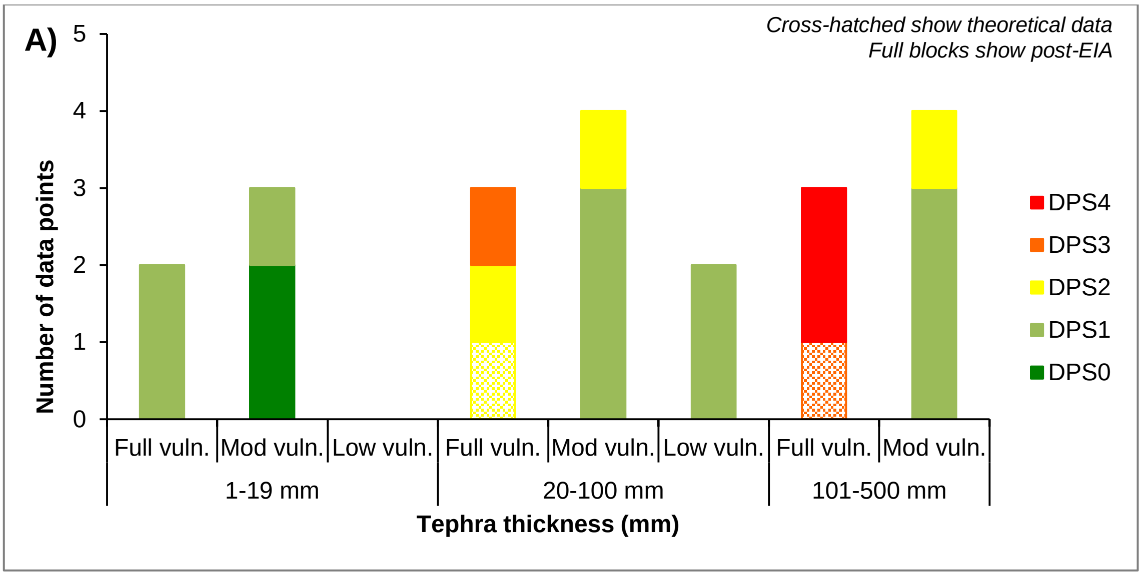


Figure 6.11: Tree fruits fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin; B) fragility functions for tree fruits.

<u>Cereals</u>

Cereals are usually grown as part a crop rotation system, which may mean different levels of maturity, leading to varying vulnerabilities that need to be taken into account.

Impacts to cereals due to tephra fall have been recorded on 19 occasions, during numerous case studies including the 1980 Mt St. Helens (Cook et al. 1981), 1995 Ruapehu (Cronin et al. 1998), 2006 Merapi (Wilson et al. 2007), 2008 Chaitén (T. M. Wilson, unpub. field notes), 2010 Tungurahua (Sword-Daniels et al. 2011) and 2014 Kelud (Blake et al. 2015) eruptions. However, despite the variety of case studies there are only two DPS3 point recorded (Fig. 6.12 a). Cereal crops are relatively vulnerable compared to fruiting and root vegetables, and tree fruits (Fig. 6.12 b). Cereals are vulnerable to impacts as tephra can easily accumulate between and around the florets and in the auricle structure (White & Hodgson 1999), but is difficult to remove. Additionally, cereal farming often relies on mechanical harvesting equipment which can suffer mechanical abrasion and clogging of air takes due to the tephra deposit (Wilson et al. 2014).



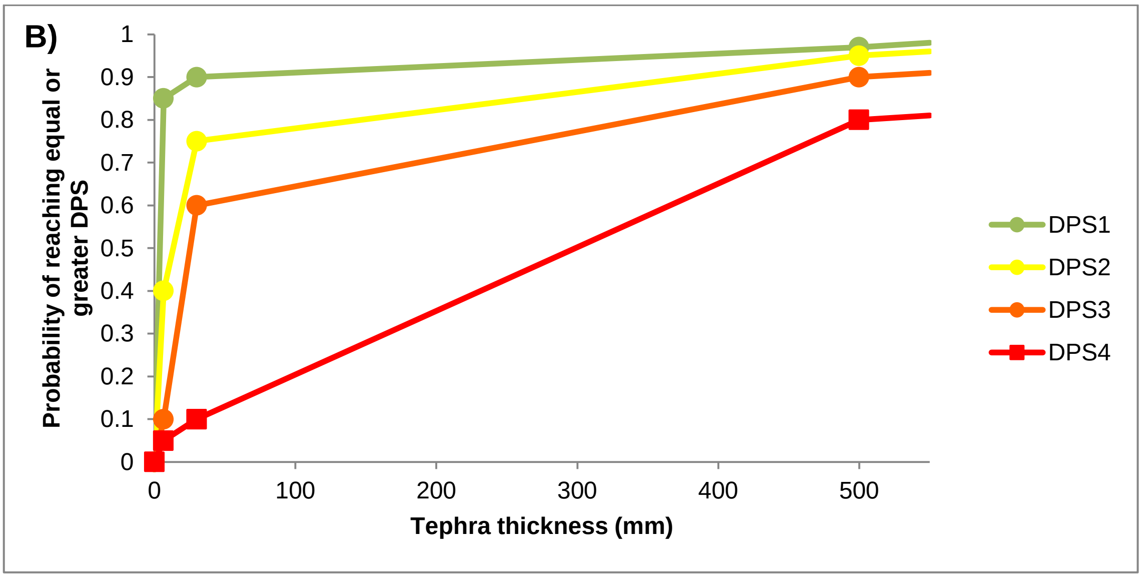


Figure 6.12: Cereal fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin; B) fragility functions for cereals.

Viticulture

Viticulture is the production of grapes, often for winemaking. Grape vines are vulnerable to tephra fall due to the delicate nature of the fruit and vine structure and their specific fertility requirements. Additionally, production and harvesting equipment is also vulnerable.

The creation of viticulture fragility function relied on previous vulnerability studies (Pevreal 2007; Wilson & Kaye 2007), with only one recorded empirical study after the 2002 Etna eruption (Barnard 2003). However, despite this limitation fragility functions are proposed using the 11 available points (Fig. 6.13 a). Viticulture is relatively vulnerable (Fig. 6.13 b) to tephra fall due to the formation of vines and grapes making tephra fall removal and cleaning difficult. Irrigation of crops is often not sufficient to remove all tephra and uneconomic hand washing may be necessary (Pevreal, 2007).

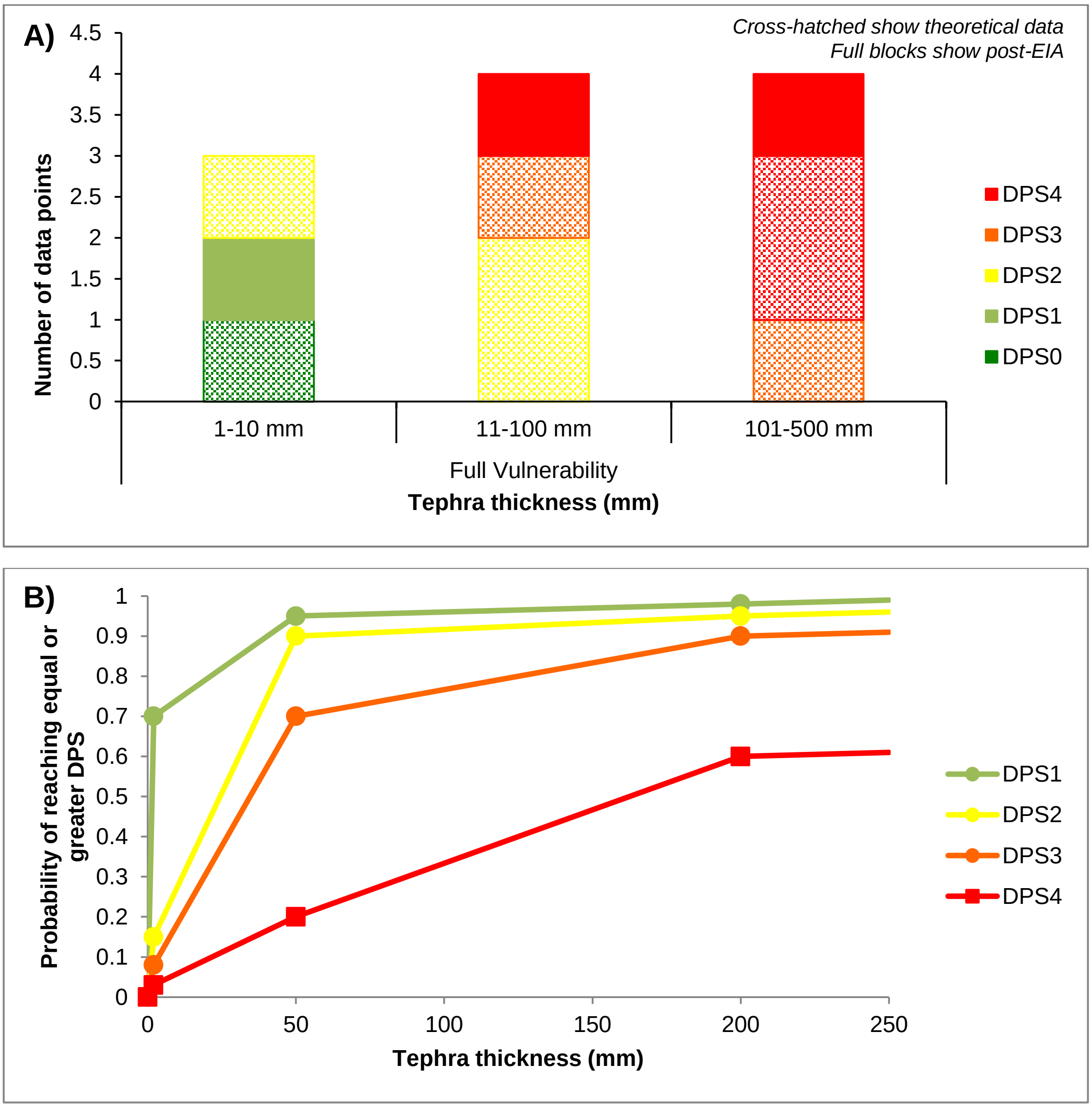


Figure 6.13: Viticulture fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin; B) fragility functions for viticulture.

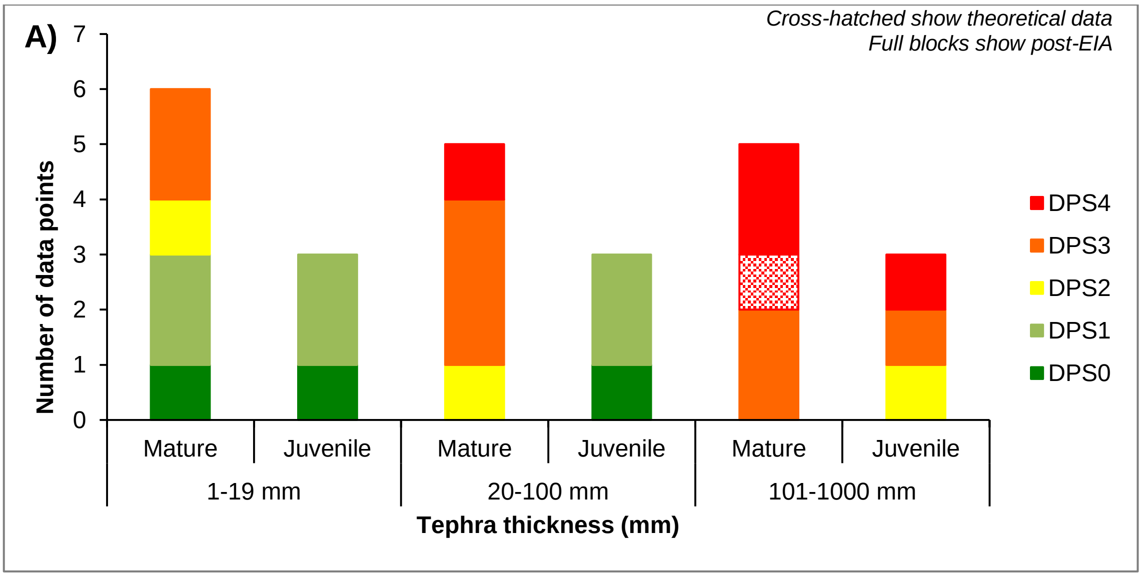
<u>Paddy farming</u>

Paddy farming of rice is unique due to the flooding of paddies after germination. Juvenile rice that is still flooded is more resilient to tephra fall as it can be re-flooded, however mature rice is much more exposed to tephra fall so suffers more severe impacts.

Fragility functions were created for mature rice crops using 16 empirical points, predominantly from post-event impact assessment studies in Indonesia (2006 Merapi, Wilson et al. 2007; and 2015 Kelud, Blake et al. 2015). The data set covers the range of

DPS well and appears to be relatively representative based on expert judgement, despite being based primarily on a single country (Fig. 6.14 a). Therefore fragility functions for rice should be relatively accurate (Fig. 6.14 b).

In order to account for the differences in vulnerability dependent on the maturity of the crop raw data for mature (16 points) and juvenile (9 points) were used to create a set of fragility functions to calculate the percentage difference in vulnerability (Fig. 6.15). The difference in vulnerability is greatest a moderate thicknesses (16-200 mm). This is because at ≤15 mm it is likely that all affected paddies will have impacts which do not reach or exceed DPS2, and at thicknesses >200 mm all affected paddies are likely to reach or exceed DPS3. However, at moderate thicknesses the stage of growth of the plant will strongly dictate the vulnerability (juvenile vulnerability at 16-200 mm is 0.56 of the mature plant vulnerability within the same thickness range) (Fig. 6.15). As there is no true season for harvesting and planting as rice is often grown in equatorial locations, the application of the vulnerability coefficient would need to be done on a case-by-case basis dependent on a specific farms' calendar.



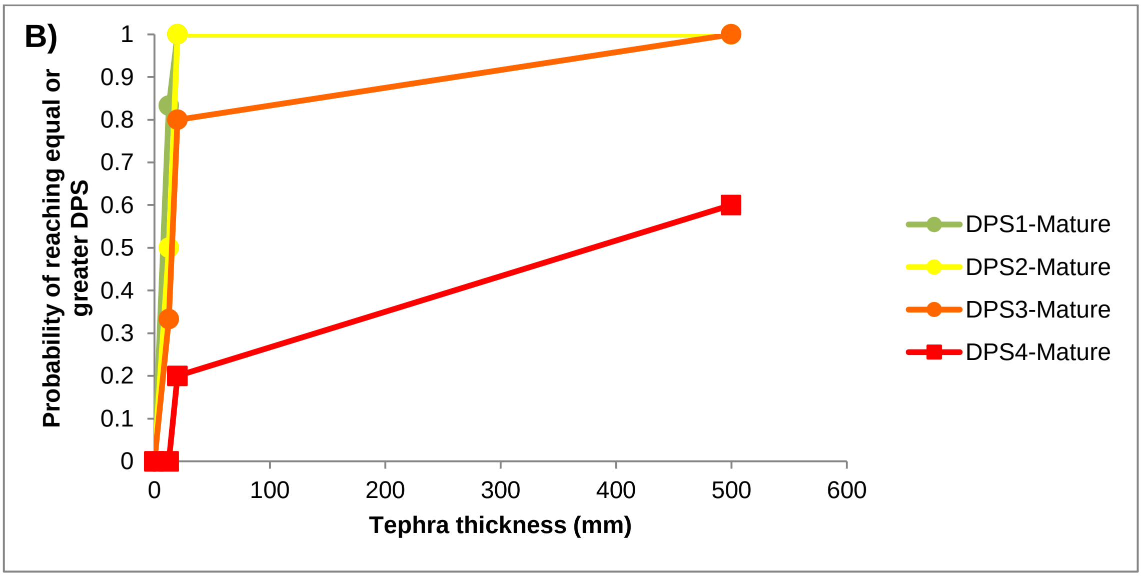
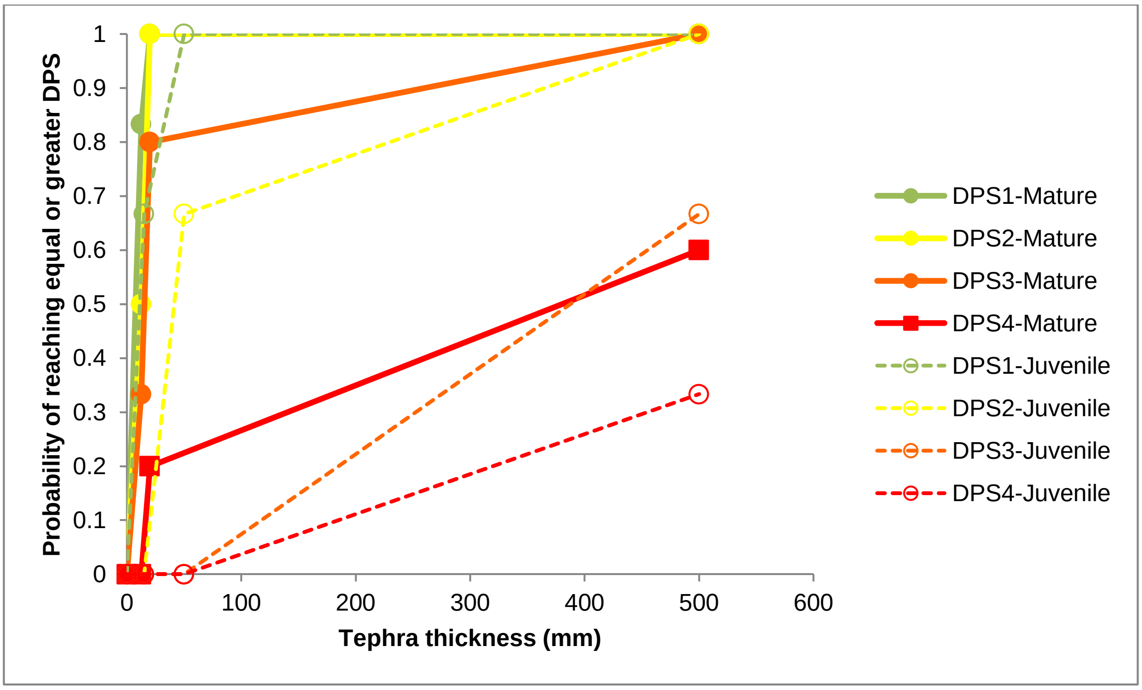


Figure 6.14: Paddy farming fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin; B) fragility functions for paddy farming.



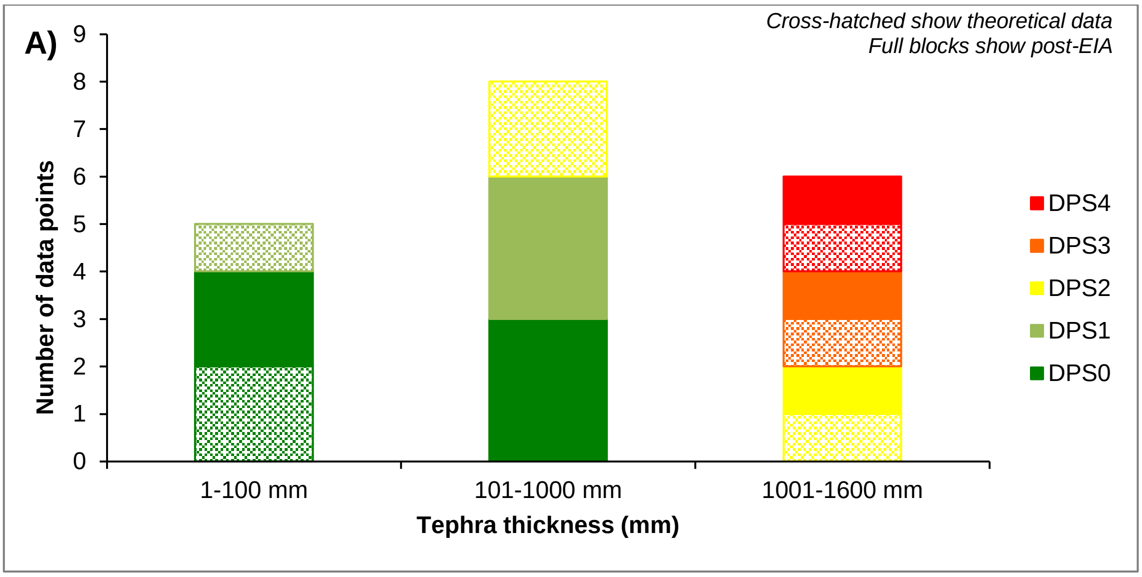
	Calculated Values	
Thickness (mm)	Mature	Juvenile
1-15	1	0.77
16-100	1	0.66
101-1000	1	0.81

Figure 6.15: Fragility functions for mature and juvenile rice crops. As mature rice is more vulnerable to tephra fall than juvenile rice crops a vulnerability coefficient was calculated from the difference between the functions.

6.3.3.3 Forestry

Forestry vulnerability is highly dependent on the ages of trees that each forestry operation is comprised of. Whilst mature trees are relatively resilient to tephra fall, seedlings and trees <10 years old are vulnerable to branch breakages and structural damage, and new plantings are vulnerable to complete structural failure or burial. Another source of vulnerability for the forestry industry is the negative impact that tephra fall has on harvesting machinery and accessibility for logging trucks. These issues, rather than actual damage to trees, cause the majority of production loss for established forestry blocks (Neild et al. 1998), and have been incorporated into the forestry DPS scheme.

The majority of forestry operations will contain trees of various ages, which complicates the formation of fragility functions for each growth stage. Additionally, the exact age of effected trees has not usually been captured during post-impact assessments, rather the overall impacts to the forestry operation as a whole. The 19 data points used to form the fragility function for forestry are from a variety of empirical case studies and previous vulnerability studies. The higher DPS states (DPS3 and DPS4) are poorly represented in the data set, probably due to the very large tephra thicknesses needed to reach these states (often >1000 mm) (Fig. 6.16 a). Expert judgement increased the likelihood of reaching or exceeding DPS3 and DPS4 to account for the dependence on road access routes for production (Fig. 6.16 b).



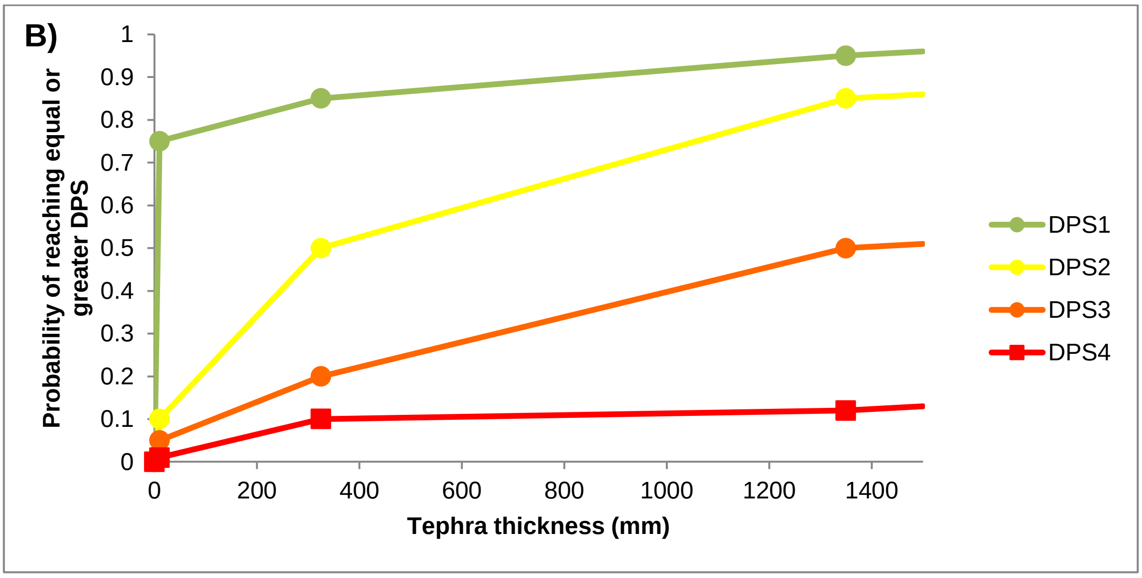


Figure 6.16: Forestry fragility functions. A) histogram showing the number of DPS data points available for each tephra thickness bin; B) fragility functions for forestry.

6.3.3.4 Greenhouses

The vulnerability of greenhouse structures to tephra fall is complex due to significant differences in construction type, materials and quality. This means that creating a standard set of DPS descriptors to apply to all of the various structures that are used as greenhouses is extremely difficult. Also, due to this diversity, gaining enough case studies of the same construction and material type to provide reasonably accurate probabilities of reaching a certain damage state would also be challenging. Previous vulnerability studies have created functions for various building typologies, however none have included greenhouses. After a review of previous vulnerability and fragility functions created for the built environment after tephra fall (notably Jenkins & Spence 2009; Maqsood et al. 2014), for the purposes of this New Zealand based study greenhouses have been represented by “large, commercial, engineered buildings” from the Global Assessment of Risk (GAR) 2015 report on Regional Vulnerability Functions) (Fig. 6.17 a). This is a generic curve that should be refined to more specific greenhouse designs and vulnerabilities when undertaking a regional risk assessment. However, for the purposes of this national level study the generic curve from the GAR report is sufficient. Unlike the fragility functions proposed for the other agricultural sectors, this greenhouse vulnerability function uses a damage index to represent impacts.

The damage indexes being the ratio between the cost to repair the structure to its pre-event condition, and the cost to completely replace the structure. The independent variable on the fragility function was converted from loading (kPa) into tephra thickness (mm) using a standard dry tephra density approximation of 1000 kg/m^3. This was due to the available probabilistic hazard model used in Section 3 being calculated in tephra thickness rather than loading (Hurst & Smith 2010). The same process was then undertaken using a density of 1500 kg/m^3 to create a curve for a wet tephra deposit (Johnston 1997).

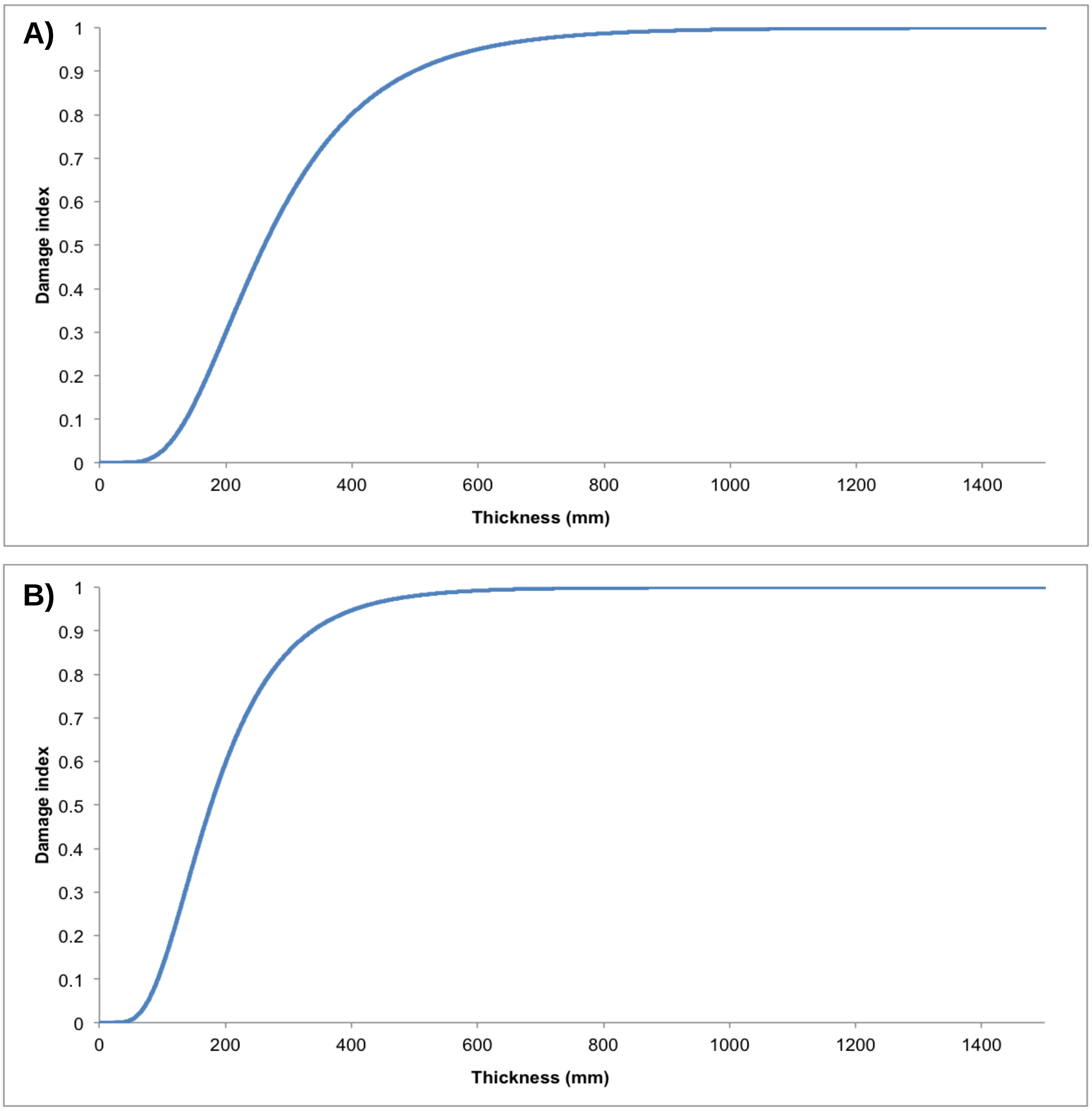


Figure 6.17: Vulnerability curve that will be used to assess risk to New Zealand greenhouses. Taken from curves proposed for large commercial, engineered buildings (Maqsood et al. 2015). Tephra thicknesses calculated from loading (kPa) using a standard density of 1000kg/m3 for dry tephra (A); and 1500kg/m3 for wet tephra (B).

6.3.4 Uncertainties and limitations

As with all studies that aim to identify overall trends in vulnerability to a hazard, there are numerous limitations and sources of uncertainty associated with the proposed fragility functions. These include:

- The limited number of observations available. Only a small number of data points (relative to other infrastructures and hazard types, i.e., buildings and earthquake shaking) could be used in the creation of the functions. This is due to the infrequent nature of large, tephra-producing volcanic eruptions, and inconsistent vulnerability data collection post-event. This is especially evident when assessing agricultural vulnerability as many previous studies have concentrated on urban impacts.
- The assumption that the available data points form an indication of a representative sample. The inclusion of expert judgement is required as it is acknowledged that it is highly unlikely that the data from post-event impact assessment and previous vulnerability studies alone is representative. However, the data is assumed to give an indication of the relative probabilities of each damage/production state occurring.
- The application of expert judgement using predefined guidelines. Although the collected data and the establishment of guidelines for expert judgement guide the adjustment of the functions, any deviation from the raw dataset could potentially increase the amount of uncertainty.
- The consideration of only one measure of hazard intensity (tephra thickness, mm). Whilst there is rationale for this (see Section 6.3.2.4), impacts will also be influenced by other hazard intensity measures such as the grain size of the deposit and the duration of the tephra fall. However, it is not possible to robustly account for these factors in the proposed functions.
- The functions do not take into account pre-event mitigative strategies or post-event recovery measures. These factors may dramatically decrease the maximum damage/production loss received by farmers after an event, but these are not considered here.

6.4 Application of fragility functions to the North Island, New Zealand

An impact assessment for the North Island of New Zealand was undertaken using a probabilistic volcanic hazard model (Hurst & Smith 2010), in order to demonstrate the applicability of the proposed fragility function suite. This assessment identified agricultural areas that have a high risk of tephra fall impacts occurring over a 500 year and a 10,000 year annual recurrence interval (ARI). The fragility functions were then applied to assess the impacts that are predicted to occur due to tephra fall from the 1995 Ruapehu, 1996 Ruapehu, and ~1315 Kaharoa eruptions. These deterministic scenarios provide an opportunity to correlate predicted impacts using the fragility functions to those that actually occurred (in the case of the Ruapehu eruptions), and also demonstrate how the functions could be applied after an event when a single set of tephra fall isopachs have been rapidly produced.

6.4.1 Methodology

6.4.1.1 Probabilistic hazard model

The Hurst & Smith (2010) probabilistic volcanic hazard model (PVHM) was used in the agricultural impact assessment using the hazard surfaces outputted by the PVHM. Using the volume erupted, column height, ash grain size distribution, and wind conditions, the PVHM uses the ASHFALL program to model single eruptions (Hurst 1994). Monte Carlo methodology is then used to randomise the variation in eruptive volumes and wind conditions (Hurst & Smith 2004). A million years of eruptions were simulated for Ruapehu, Ngauruhoe/Tongariro, Taranaki, Taupo, Okataina, Mayor Island, and the Auckland Volcanic Field (Fig. 6.18), and a count of the number of times a particular tephra thickness was reached or exceeded calculated (Hurst & Smith 2010). These volcanic centres were chosen as they are recently active, have the potential to produce singnificant volumes of tephra, and will likely impact the New Zealand mainland (taking into account tephra volume and prevailing wind directions) (Hurst & Smith 2010). By using single event exceedences the PVHM shows the most likely tephra fall scenario that will occur at a given point over a specific return period. The number of exceedences was then translated into return period grid files for 500 (i.e., the thickness exceedence with an annual probability of 1/500) and 10,000 year ARI (i.e., the thickness exceedence with an annual probability of 1/10,000) (Hurst & Smith 2004). These were then used as the hazard layer in our impact modelling for North Island agriculture.

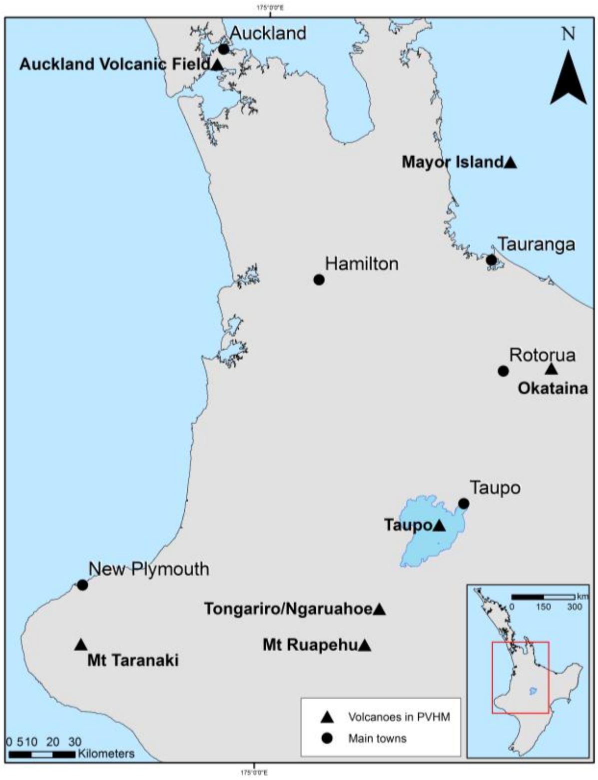


Figure 6.18: North Island volcanoes and volcanic centres included in the Hurst & Smith (2010) probabilistic volcanic hazard model.

6.4.1.2 Agriculture exposure inventory

In order to perform the impact assessments a compatible agricultural inventory dataset was required. The fragility functions were developed to best capture different agricultural types and their associated vulnerabilities, but also to be applied as a risk assessment tool with two available New Zealand agricultural inventory databases. These are the AgriBase® agricultural dataset (AssureQuality 2014) and the Land Information New Zealand (LINZ) land cover version 4.0 (Landcare Research 2014) and large building (for greenhouses) datasets (LINZ 2015). Using both these datasets allowed for the division of agricultural inventories into the categories represented by the proposed fragility functions, as shown in Table 6.7.

Table 6.7: Asset inventory source information for risk assessment.

Sector	Type	Agribase codes	Agribase descriptors	LINZ classification*	LRIS classification^
Pastoral	High intensity	BEF, DEE, HOR, SHP, SNB	Beef cattle, deer, horse, sheep, mixed sheep/beef	-	-
	Dairying	DAI, DRY	Dairy cattle, dairy dry	-	-
Horticul-ture	Root vegetables	VEG	Vegetable growing	Short-rotation cropland	-
	Leafy vegetables	VEG	Vegetable growing	-	-
	Fruit	FRU	Fruit growing	-	-
	Tree fruit	FRU	Fruit growing	Orchards and vineyards	-
	Cereals	ARA	Arable cropping	-	-
	Viticulture	VIT	Viticulture	-	-
	Greenhouses		-	-	Greenhouses
Forestry		FOR	Forestry	-	-

*LINZ (Land Information New Zealand) only used where Agribase dataset does not provide the required separations.
^LRIS large buildings database used for greenhouses

6.4.1.3 Assessment Methodology

Tephra thicknesses were obtained from a centroid point within each farm polygon (provided by the Agribase® dataset) using geographic information systems (GIS). For this assessment 500 and 10,000 year ARI hazard surfaces were used, as they are most commonly applied when assessing the seismic hazard (Uma et al. 2013) and were the return periods for which reliable probabilistic tephra model data was available (Hurst & Smith 2010). As shown in Figure 6.19, using the given tephra thickness for each farm, the probability of reaching each DPS was calculated from the fragility function specific to the farm type of that polygon. Using the probabilities at the thickness for each point 10000 DPS were randomly sampled in order to take into account the uncertainties associated with each fragility function. Then a weighted average DPS value was calculated and rounded to the nearest whole number. This gave an average likely DPS value for each farm polygon. These were then mapped to the North Island for both return periods, and the amount of land falling within each DPS calculated.

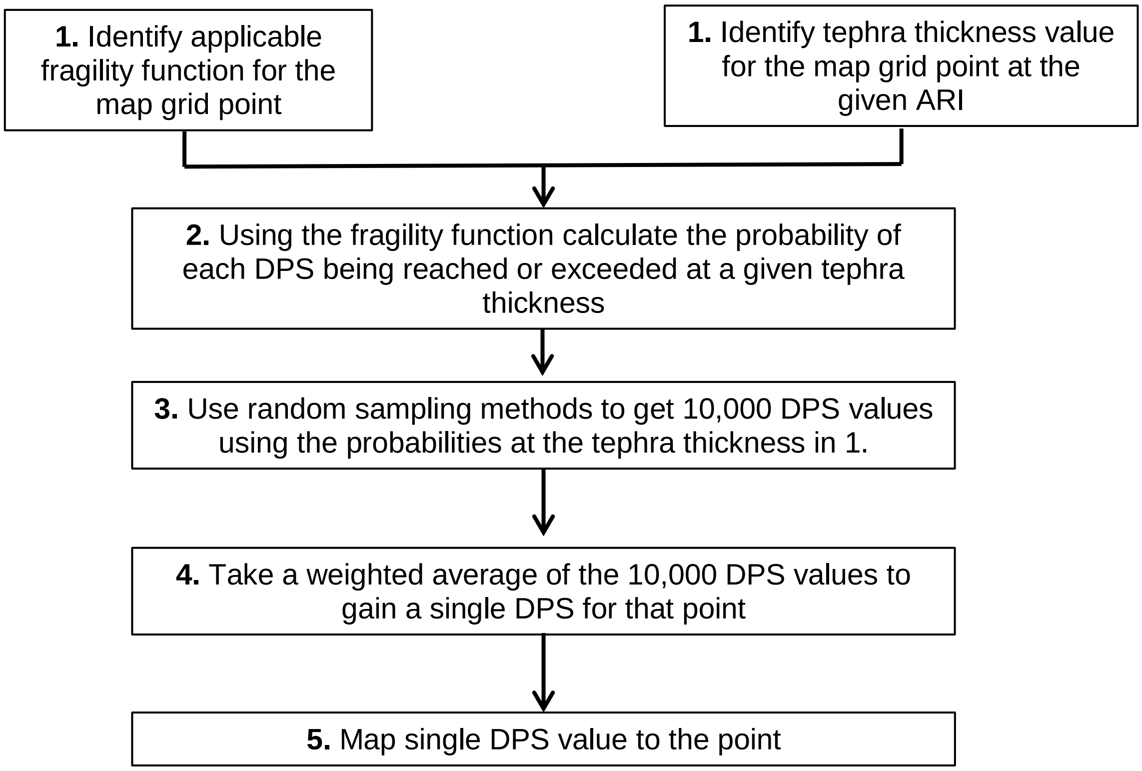


Figure 6.19: Methodology for predicting the DPS at map grid points.

For the greenhouse assessment a centroid point was assigned to each greenhouse polygon. The tephra thickness at each centroid point was then used to find the damage index, using the Global Assessment of Risk 2015 report on Regional Vulnerability Functions (Maqsood et al. 2014) curve (Fig. 6.17). These damage indexes were then binned into five ranges (0.2 intervals), colour coded, and mapped using GIS.

The percentage of production loss that would occur in each DPS was estimated for each of the agricultural sectors (pastoral/dairying, horticulture, and forestry). This allowed for a preliminary economic assessment to be undertaken, using the estimated profit per hectare per year values gathered from various sources (Bargle et al. 2013; DairyNZ Limited 2014; Ministry of Agriculture and Forestry 2010; The New Zealand Institute for Plant and Food Research 2013).

In order to assess the application of the fragility functions in a tephra fall event scenario, an impact assessment was performed for current farm distribution using the 1995 and 1996 Ruapehu, and the ~1315 AD Kaharoa tephra fall events. The 1995 and 1996

Ruapehu events were chosen as they are the most recent tephra fall events to impact New Zealand agriculture in a significant way. This meant that there was information recorded on the impacts to local agricultural systems that could be compared to the models findings. Kaharoa is a relatively well-mapped large-scale, intra-caldera scenario that could occur at many of the caldera complexes in the North Island. Isopach maps were taken from Cronin et al. (1998) for the Ruapehu events, and Sahetapy-Engel et al. (2014) for the Kaharoa tephra fall. The same empirical method (described above) was used to assign a thickness to each farm, and calculate a DPS value. The Ruapehu events were assessed using the appropriate vulnerability coefficient for the time of the eruption (i.e., October 1995 and June 1996).

6.4.2 Results and discussion

The volcanic impacts to farms in the North Island was mapped as a DPS exceedence. This exceedence shows the likely DPS caused by the hazard surface for an ARI of 500 and 10,000 years from the North Island volcanoes considered in the probabilistic tephra fall model (Hurst & Smith 2010).

Impact assessments for all agricultural sectors showed an increase in DPS (or damage index) with an increase in return period and therefore tephra thicknesses, with areas of high risk concentrated to the east of Ruapehu, Tongariro, Taranaki and the Taupo, and becoming evident around Okataina and the Auckland Volcanic Field when considering ARI of >500 years.

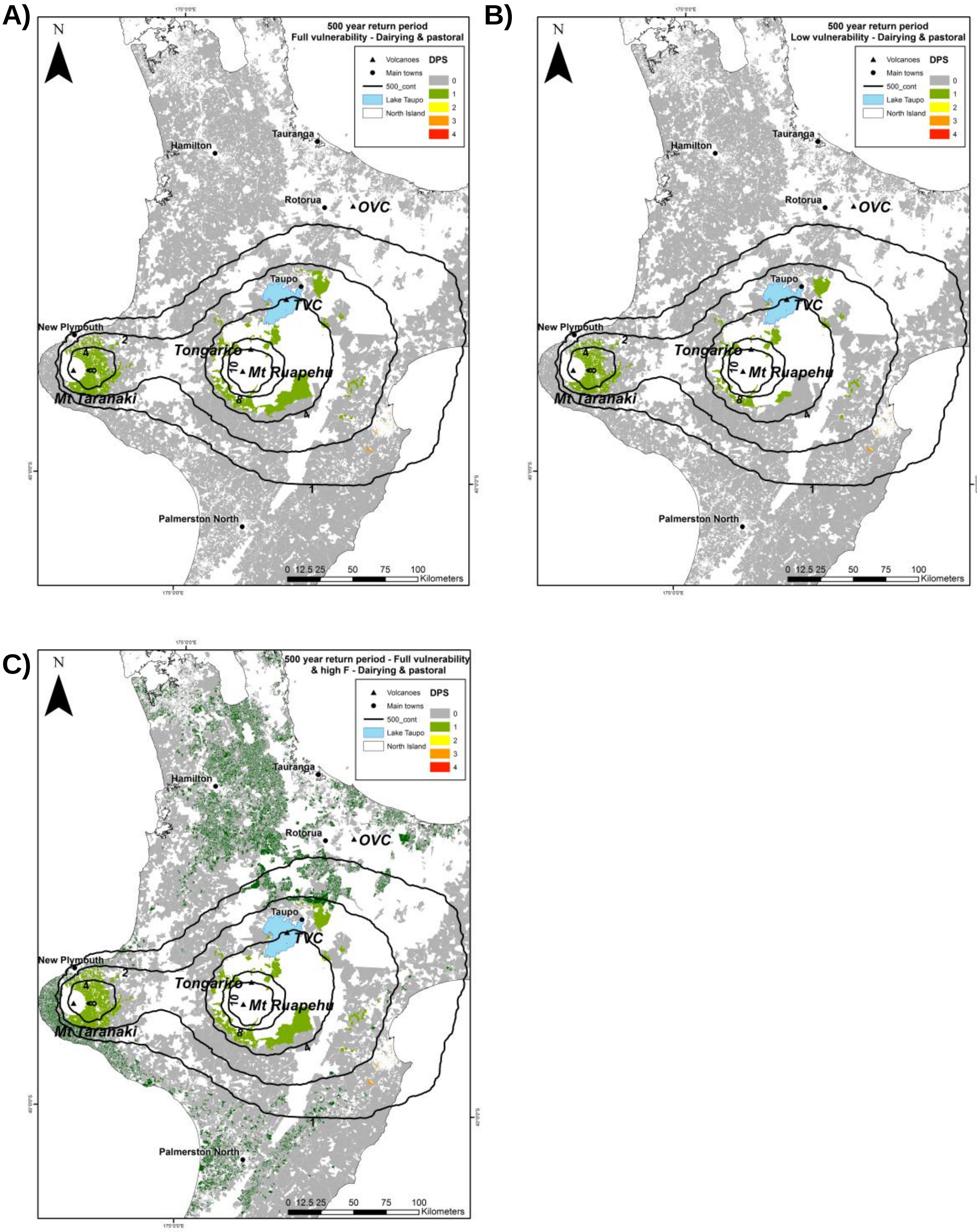


Figure 6.20: Impact assessment for pastoral farming systems due to a 500 year ARI tephra hazard surface. A) DPS at a time of full vulnerability; B) DPS at a time of low vulnerability; and C) DPS at a time of full vulnerability when the tephra contains high levels of leachable fluoride (>150 mg/kg).

6.4.2.1 Pastoral and dairying

Pastoral and dairy farms are the most common forms of agriculture within the North Island of New Zealand covering 5.3 million and 1.4 million hectares, respectively (Table 6.8). A risk analysis for pastoral and dairy farms in the North Island shows that for a 500 year return period tephra fall exceedence, during a time of full vulnerability, there are three main areas that will be impacted by the tephra fall. These are to the east of Mt. Taranaki (which is an area of predominantly dairy farming), around Mt. Ruapehu and Tongariro (dominated by sheep farming), and a concentrated area of dairying to the east of Taupo (Fig. 6.20a). The model predicts that the area affected by a 500 year ARI tephra hazard surface covers ~132,000 ha of dairying (9.2%) and ~170,000 ha of pastoral land (3.2%) and do not exceed DPS1 (Table 6.8), meaning that the majority of losses (~90%) could be absorbed within the normal production fluctuations within a year (Fig. 6.19a). However, there could still be large economic losses for the region over a 500 year return period with the estimated costs of a 10% decrease in production for a year, being $24 million (dairying) and $13 million (pastoral) (Table 6.9 a). These losses would occur in dairy farms mostly due to the use of supplementary feed providing a lower nutritional value, causing milking rates to decrease, coupled with any possible issues with milking equipment due to tephra contamination. Pastoral farming losses would be caused by the reliance on supplementary feed, and additional cultivation work reducing the profitability of the land for the year. Additionally, for both types any time and money spent on removing the tephra or cultivating could lead to the profit margin (per ha of land) decreasing.

In order to assess the influence that the timing of the tephra fall has on impacts, a low vulnerability risk assessment was also undertaken for a 500 year ARI tephra hazard surface (Fig. 6.20b). This vulnerability level represents an eruption that takes place during autumn to mid-winter (Fig. 6.2). As with the full vulnerability assessment, the highest impacts were classified as DPS1, however the reduction in vulnerability resulted in the model estimating a slightly smaller area affected, with ~115,000 ha of dairying (8.0%) and ~70,000 ha of pastoral land (1.3%) in DPS1 (Table 6.10). This is because as the tephra fall does not occur during the sensitive spring pasture growth period, or during the summer when vegetation metabolic rates are at there highest (White &

Hodgson 1999). This means higher tephra thicknesses can occur before a farm is impacted enough to be best described as DPS1. Conversely, an impact assessment was also undertaken during a time of full vulnerability when the tephra deposit also contains high levels of environmentally available fluoride (>150 mg/kg) (Fig. 6.20c). Pastoral and dairy farms are less resilient to tephra with high F, as livestock are vulnerable to fluoride toxicity which manifests as chronic or acute fluorosis (see Section 6.3.2.5). Using the fluoride coefficient to modify the fragility functions input into the risk assessment, causes an increase in the area of farms reaching DPS1, with ~135,000 ha of dairying (9.5%) and ~177,000 ha of pastoral land (3.3%) (Table 6.11). This is due to the possible occurrence of fluorosis decreasing production rates, even at relatively low tephra thicknesses. This effect would be exacerbated by the caution farmers would be forced to exercise if high fluoride levels are recorded, whereby supplementary feed usage would be much higher and prolonged, and tephra removal and cultivation would be widespread, in order to manage the risk of fluorosis. These actions would occur in areas where small tephra thicknesses would not usually necessitate widespread cultivation or supplementary feed use, however the toxicity risk would be the main driver. This greater expenditure will lead to farmland being much less profitable for the year.

Table 6.8: Land cover (ha) and percentage land within each DPS at full vulnerability for the 500 year ARI tephra hazard surface.

Agricultural sector	DPS0		DPS1		DPS2		DPS3		DPS4		
	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Total Area (ha)
Cereals	27918.1	99.9	21.6	0.1	0.0	-	0.0	-	0.0	-	27939.7
Fruit	3450.9	98.2	63.1	1.8	0.0	-	0.0	-	0.0	-	3513.9
Tree fruit	33768.3	100.0	0.0	0.0	0.0	-	0.0	-	0.0	-	33768.3
Root vegetables	11046.7	99.0	113.0	1.0	0.0	-	0.0	-	0.0	-	11159.7
Leafy vegetables	1976.0	98.3	33.2	1.7	0.0	-	0.0	-	0.0	-	2009.2
Viticulture	4551.1	48.3	4873.7	51.7	7.4	0.1	0.0	-	0.0	-	9432.2
Pastoral	5147102.3	96.8	170318.3	3.2	0.0	-	0.0	-	0.0	-	5317420.6
Dairying	1297478.1	90.8	131657.0	9.2	0.0	-	0.0	-	0.0	-	1429135.1
Forestry	982076.5	97.5	25296.9	2.5	0.0	-	0.0	-	0.0	-	1007373.5
Total Area (ha)	7509368.2	95.8	332376.7	4.2	7.4	0.0	0.0	0.0	0.0	0.0	7841752.3

Table 6.9: Tables estimating the potential financial losses (in NZD) in the first year after an eruption during a time of full vulnerability for a A) 500 year and B) 10,000 year ARI tephra hazard surface.

A) 500 year ARI		**Cereals**	**Fruit**	**Tree fruit**	**Root vegetables**	**Leafy vegetables**	**Viticulture**	**Pastoral**	**Dairying**	**Forestry***
DPS	**Production per ha ($)**	1,000[a]	1,900[a]	4,400[a]	1,500[b]	3,500[c]	4,000[a]	800[a]	1,830[d]	25,000[e]
0	Area (ha)	27,918.1	3,450.9	33,768.3	11,046.7	1,976.0	4,551.1	5,147,102.3	1,297,478.1	9,82,076.5
	Approx % loss within DPS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
1	Area (ha)	21.6	63.1	0.0	113.0	33.2	4873.7	170318.3	131,657.0	25,296.9
	Approx % loss within DPS	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	0.0
	Approx $ losses	**2,155.4**	**11,983.6**	**0.0**	**16,943.2**	**11,623.5**	**1,949,468.2**	**13,625,464.0**	**24,093,229.5**	**0.0**
2	Area (ha)	0.0	0.0	0.0	0.0	0.0	7.4	0.0	0.0	0.0
	Approx % loss within DPS	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	10.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**8,884.8**	**0.0**	**0.0**	0.0
3	Area (ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx % loss within DPS	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	50.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
4	Area (ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx % loss within DPS	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Total losses	**$2,155.4**	**$11,983.6**	**$0.0**	**$16,943.2**	**$11,623.5**	**$1,958,353.0**	**$13,625,464.0**	**$24,093,229.5**	**$0.0**
									Total losses for 500 year hazard surface:	**~$38 million**

B) 10,000 year ARI		**Cereals**	**Fruit**	**Tree fruit**	**Root vegetables**	**Leafy vegetables**	**Viticulture**	**Pastoral**	**Dairying**	**Forestry***
DPS	**Production per ha ($)**	1,000[a]	1,900[a]	4,400[a]	1,500[b]	3,500[c]	4,000[a]	800[a]	1,830[d]	25,000[e]
0	Area (ha)	1,665.2	656.1	5,852.8	1,001.7	290.0	28.1	585,205.2	181,764.1	144,274.6
	Approx % loss within DPS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
1	Area (ha)	5,856.3	1,041.6	26,641.5	4,849.4	327.3	2,214.7	2,336,802.9	570,517.8	858,444.0
	Approx % loss within DPS	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	0.0
	Approx $ losses	**585,630.4**	**197,909.2**	**11,722,279.7**	**727,411.9**	**114,567.8**	**885,866.7**	**186,944,231.8**	**104,404,759.6**	**0.0**
2	Area (ha)	0.0	0.0	0.0	3,647.8	1,330.1	45.9	2,249,822.1	591,600.2	4,654.8
	Approx % loss within DPS	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	10.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**1,641,491.7**	**1,396,645.9**	**55,023.7**	**539,957,293.8**	**324,788,512.9**	**11,637,070.4**
3	Area (ha)	17,380.7	1,401.1	1,273.9	1,568.5	0.0	7,107.4	92,899.6	50,631.1	0.0
	Approx % loss within DPS	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	50.0
	Approx $ losses	**10,428,422.3**	**1,597,216.9**	**3,363,164.9**	**1,411,683.6**	**0.0**	**17,057,737.4**	**44,591,791.1**	**55,592,936.9**	**0.0**
4	Area (ha)	3,037.5	415.2	0.0	92.3	61.8	36.2	23,772.2	34,621.9	0.0
	Approx % loss within DPS	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Approx $ losses	**3,037,475.3**	**788,786.0**	**0.0**	**138,462.8**	**216,296.1**	**144,905.0**	**19,017,767.4**	**63,358,101.6**	0.0
Total losses		**$14,051,528.0**	**$2,583,912.1**	**$15,085,444.7**	**$3,919,050.1**	**$1,727,509.9**	**$18,143,532.8**	**$790,511,084.1**	**$548,144,311.0**	**$11,637,070.4**

*Forestry production per ha is for harvestable trees only. **Total losses for 10,000 year hazard surface: ~$1,405 million**

a. ANZ 2013
b. Horticulture NZ 2013
c. Ministry of Primary Industries 2011
d. Dairy NZ 2013

Table 6.10: Land cover (ha) and percentage land within each DPS at low vulnerability for the 500 year ARI tephra hazard surface.

Agricultural sector	DPS0		DPS1		DPS2		DPS3		DPS4		
	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Total Area (ha)
Cereals	27939.7	100.0	0.0	0.0	0.0	-	0.0	-	0.0	-	27939.7
Fruit	3513.9	100.0	0.0	0.0	0.0	-	0.0	-	0.0	-	3513.9
Tree fruit	33768.3	100.0	0.0	0.0	0.0	-	0.0	-	0.0	-	33768.3
Root vegetables	11080.6	99.3	79.0	0.7	0.0	-	0.0	-	0.0	-	11159.7
Leafy vegetables	2009.2	100.0	0.0	0.0	0.0	-	0.0	-	0.0	-	2009.2
Viticulture	9424.8	99.9	7.4	0.1	0.0	-	0.0	-	0.0	-	9432.2
Pastoral	5247520.6	98.7	69900.1	1.3	0.0	-	0.0	-	0.0	-	5317420.6
Dairying	1314467.7	92.0	114667.5	8.0	0.0	-	0.0	-	0.0	-	1429135.1
Forestry	982076.5	97.5	25296.9	2.5	0.0	-	0.0	-	0.0	-	1007373.5
Total Area (ha)	7631801.3	97.3	209950.9	2.7	0.0	0.0	0.0	0.0	0.0	0.0	7841752.3

Table 6.11: Pastoral and dairying land cover (ha) and percentage land within each DPS at full vulnerability and high leachable fluoride concentrations (>150 mg/kg) for the 500 year ARI tephra hazard surface.

Agricultural sector	DPS0		DPS1		DPS2		DPS3		DPS4		
	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Total Area (ha)
Pastoral	5140159.2	96.7	177261.5	3.3	0.0	-	0.0	-	0.0	-	5317420.6
Dairying	1293750.7	90.5	135384.4	9.5	0.0	-	0.0	-	0.0	-	1429135.1
Total Area (ha)	6433909.9	95.4	312645.9	4.6	0.0	0.0	0.0	0.0	0.0	0.0	6746555.8

Pastoral and dairying impacts are much more severe when considering a 10,000 year ARI tephra hazard surface. For all seasonal and fluoride vulnerability types, impacts range from DPS0 in Northland and a small area near Wellington, to DPS4 in farms immediately adjacent to Mt. Taranaki, Taupo, and Okataina (Fig. 6.21). The model predicts that the economic ramifications for New Zealand would be severe over a 10,000 year return period, where at a time of full vulnerability there could be ~$791 million worth of loss to the pastoral sector and ~$548 million to dairying (Table 6.9 b). 2.4% of dairying and 0.4% of pastoral land in the North Island is categorised within DPS4 (Table 6.12), indicating that a farm needs widespread mitigation, suffers from >50% animal deaths and may even require abandonment in the long-term. This would be catastrophic for farmers within these areas, where it is likely that long-term financial, practical, and possibly psychological support will be required. This is also likely to apply to farms within DPS3 (~51,000 ha of dairying and ~93,000 ha of pastoral, Table 6.12). The most commonly occurring impacts fall into DPS1 (39.9% of dairying and 44.2% of pastoral farms) and DPS2 (41.4% dairying, 42.5% pastoral), which would mean a large amount of supplementary feed would be required across the whole of the central North Island (Table 6.12; Fig. 6.21 a). It is likely that this demand will not be fully met leading to rationing of supplies. Some dairy farmers would likely dry-off livestock to decrease nutritional requirements, and to prevent milk dumping, as road transport would be severely impacted as well (Wilson & Cole 2007; Wilson et al. 2009). Due to the large amount of the North Island affected, emergency managers would need to prioritise resources to aid certain key areas, rather than having the ability to provide full support to all affected farms.

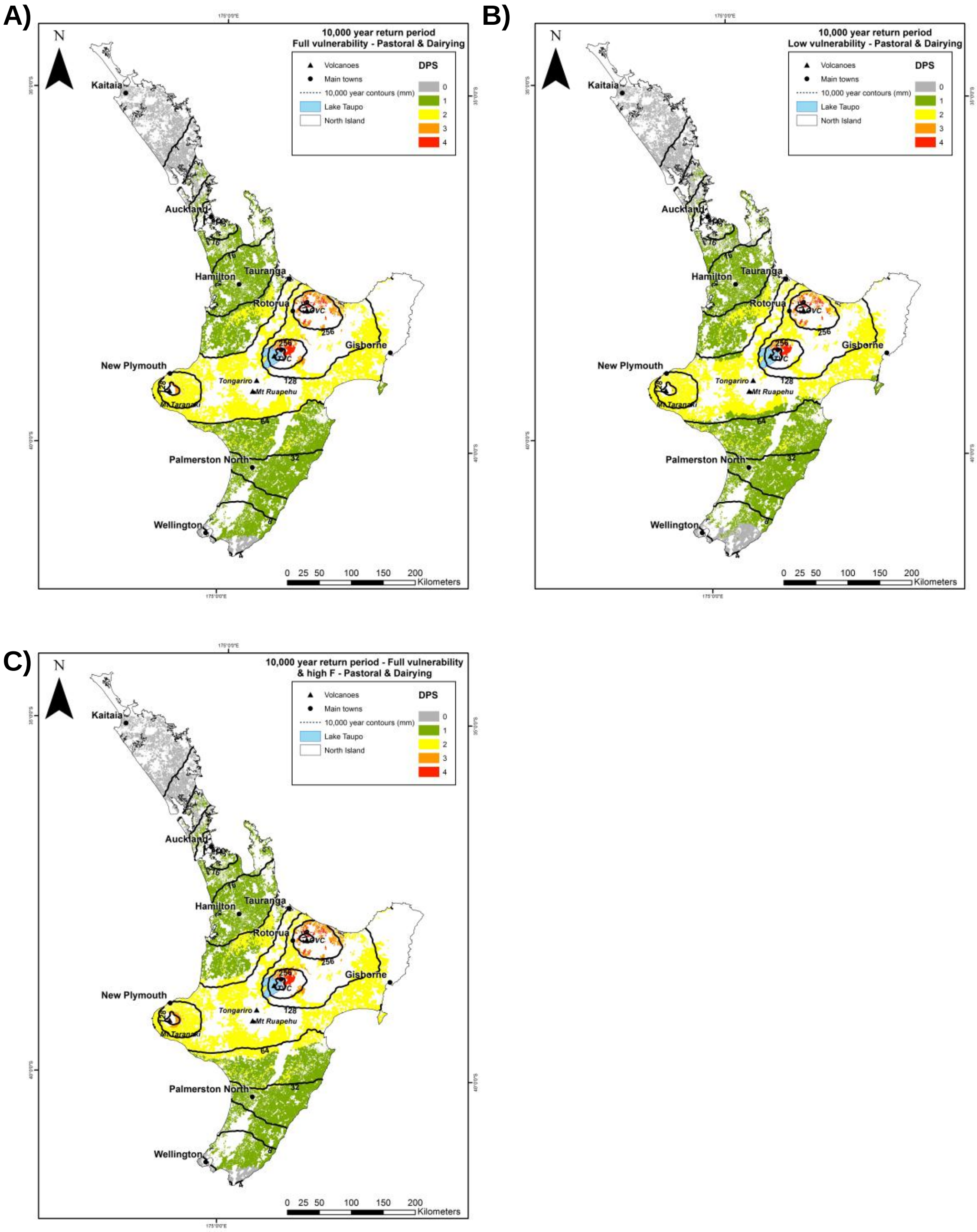


Figure 6.21: Risk assessment for pastoral farming systems due to a 10,000 year ARI tephra hazard surface. A) DPS at a time of full vulnerability; B) DPS at a time of low vulnerability; and C) DPS at a time of full vulnerability when the tephra contains high levels of leachable fluoride (>150 mg/kg).

Table 6.12: Land cover (ha) and percentage land within each DPS at full vulnerability for the 10,000 year ARI tephra hazard surface.

Agricultural sector	DPS0		DPS1		DPS2		DPS3		DPS4		Total Area (ha)
	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	
Cereals	1665.2	6.0	5856.3	21.0	0.0	-	17380.7	62.2	3037.5	10.9	27939.7
Fruit	656.1	18.7	1041.6	29.6	0.0	-	1401.1	39.9	415.2	11.8	3513.9
Tree fruit	5852.8	17.3	26641.5	78.9	0.0	-	1273.9	3.8	0.0	-	33768.3
Root vegetables	1001.7	9.0	4849.4	43.5	3647.8	32.7	1568.5	14.1	92.3	0.8	11159.7
Leafy vegetables	290.0	14.4	327.3	16.3	1330.1	66.2	0.0	-	61.8	3.1	2009.2
Viticulture	28.1	0.3	2214.7	23.5	45.9	0.5	7107.4	75.4	36.2	0.4	9432.2
Pastoral	614123.9	11.5	2336802.9	43.9	2249822.1	42.3	92899.6	1.7	23772.2	0.4	5317420.6
Dairying	181764.1	12.7	570517.8	39.9	591600.2	41.4	50631.1	3.5	34621.9	2.4	1429135.1
Forestry	144274.6	14.3	858444.0	85.2	4654.8	0.5	0.0	-	0.0	-	1007373.5
Total Area (ha)	949656.4	12.1	3806695.6	48.5	2851100.8	36.4	172262.3	2.2	62037.1	0.8	7841752.3

Table 6.13: Land cover (ha) and percentage land within each DPS at low vulnerability for the 10,000 year ARI tephra hazard surface.

Agricultural sector	DPS0		DPS1		DPS2		DPS3		DPS4		Total Area (ha)
	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	
Cereals	7090.8	25.4	430.6	1.5	1744.7	6.2	15636.0	56.0	3037.5	10.9	27939.7
Fruit	1697.7	48.3	404.1	11.5	0.0	-	1022.3	29.1	389.7	11.1	3513.9
Tree fruit	32494.4	96.2	0.0	-	1132.1	3.4	141.8	0.4	0.0	-	33768.3
Root vegetables	9498.8	85.1	0.0	-	0.0	-	1568.5	14.1	92.3	0.8	11159.7
Leafy vegetables	319.3	15.9	298.0	14.8	1330.1	66.2	61.8	3.1	0.0	-	2009.2
Viticulture	2242.7	23.8	45.9	0.5	27.0	0.3	7080.4	75.1	36.2	0.4	9432.2
Pastoral	719888.8	13.5	2468552.3	46.4	2048884.3	38.5	56323.0	1.1	23772.2	0.4	5317420.6
Dairying	237493.2	16.6	514788.7	36.0	635127.7	44.4	7103.6	0.5	34621.9	2.4	1429135.1
Forestry	144274.6	14.3	858444.0	85.2	4654.8	0.5	0.0	-	0.0	-	1007373.5
Total Area (ha)	1155000.3	14.7	3842963.7	49.0	2692900.8	34.3	88937.5	1.1	61949.9	0.8	7841752.3

Table 6.14: Pastoral and dairying land cover (ha) and percentage land within each DPS at full vulnerability and high leachable fluoride concentrations (>150 mg/kg) for the 10,000 year ARI tephra hazard surface.

	DPS0		DPS1		DPS2		DPS3		DPS4		Total Area (ha)
Agricultural sector	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	
Pastoral	598578.0	11.3	2120125.3	39.9	2482045.5	46.7	92899.6	1.7	23772.2	0.4	5317420.6
Dairying	180805.3	12.7	507654.2	35.5	628424.3	44.0	77629.5	5.4	34621.9	2.4	1429135.1
Total Area (ha)	779383.3	11.6	2627779.5	38.9	3110469.8	46.1	170529.0	2.5	58394.1	0.9	6746555.8

Owing to the large amount of tephra deposited proximal to the active volcanic areas during a 10,000 year ARI, the number of farms within DPS4 is not influenced by the time of year the eruption occurs in (Table 6.13). However, the proportion of farms within DPS3 is significantly decreased if the eruption occurs during a time of low vulnerability (Fig. 6.21b), and the overall percentage of farms with impacts (i.e., >DPS0) is lower (86% dairying impacted at full vulnerability, 86.9% at low; 87.3% pastoral impacted at full vulnerability, 83.4% at low; Table 6.13). This means a decrease in the number of farms needing external feed supplies, and also an increase in unaffected farms that may be able to help provide supplementary feed. The most noticeable difference when performing the assessment for a high F concentration tephra is the movement of pastoral farms from DPS1 to DPS2, and the increase in the number of dairy farms at DPS2 and 3 (Table 6.14; Fig. 6.21 c). As discussed for the 500 year event assessment, the occurrence of fluoride not only causes livestock toxicity, but also influences how pro-active the farmer is in undertaking mitigative actions. If the large 10,000 year return period tephra fall also contains high leachable F concentrations, there would be further pressure on already stretched machinery, water and feed supplies. Widespread, pro-active recovery strategies would need to be put in place rapidly to try to minimise losses, including: livestock evacuations, supplementary feed programmes, and government grants for re-seeding and re-establishing pasture.

6.4.2.2 Horticulture

Similarly to the pastoral and dairying risk assessment, horticultural impacts over a 500 year ARI tephra hazard surface affect a relatively small proportion of the North Island (≤1.8%) and predominantly are only up to DPS1 in severity (Fig. 6.22a). However, viticulture is the notable exception, where over 50% is within DPS1 and 0.1% reaches DPS2 (Table 6.8). This is due to the relative vulnerability of viticulture systems due to the sensitivity of the fruit, the vine structure, and the harvesting and processing equipment (Pevreal 2007). Additionally, a greater percentage is also impacted, as viticulture is concentrated in the Hawkes Bay region, which is affected by a 500 year, return period tephra fall, whereas other horticulture sectors more frequently occur in areas outside of the tephra depositional zone. After a 500 year tephra fall it is likely that many horticulturalists will be able to manage the impacts on a practical level, however, they may require some financial aid to cover the shortfall on a slightly less productive harvest. Financial losses are estimated to be the greatest for the viticulture industry (~$1.9 million for the first year) due to the high vulnerability and high value product. These are three orders of magnitude lower for the other horticultural sectors (Table 6.9 a).

Using the theoretical seasonal coefficients scheme proposed for horticulture (Fig. 6.2), a impact assessment for horticultural sectors was also performed for a 500 year ARI tephra hazard surface, during a time of low seasonal vulnerability (Fig. 6.22b). One issue is that seasonal vulnerabilities do not occur uniformly across the horticultural sectors (Fig. 6.2). This could potentially mean that various vulnerabilities would need to be taken into account depending on the specific sector and timing of the eruption. However, for the purposes of this assessment it is assumed that the event occurs during a time when all sectors are at their lowest vulnerability (i.e., mid-spring to mid-summer). This eliminates any impacts (no land >DPS0) for cereals, fruit, tree fruit, and leafy vegetables. The model predicts that 0.7% of the North Island's root vegetables remained at DPS1, however this does not indicate a higher vulnerability compared to the other types of horticulture, rather the location of root vegetable farms immediately to the north of Mt. Taranaki and to the southwest of Mt. Ruapehu. Viticulture vulnerability was substantially reduced with just 0.1% falling within DPS1 (Table 6.10). If a 500 year event was to occur it is likely that the horticulture industry would continue to function with little disruption.

A horticultural impact assessment for a 10,000 year ARI tephra hazard surface was also considered. At full vulnerability all horticultural sectors, except the more resilient tree fruits, have farms that are classified as DPS4 (Fig. 6.22c). This means that 10.9% of cereal growing land, 11.8% of fruit, 0.8% of root vegetables, 3.1% of leafy vegetables, and 0.4% of viticulture within DPS4 will suffer a >90% reduction in yield and take more than one year to recover (Table 6.13). A further 14.1 to 62.2% of these sectors is classified as DPS3, meaning significant mitigation needed and ~60% reduction in yield. This is a significant economic cost, with a $55 million loss in horticultural profit predicted in the first year after the eruption (Table 6.9 b). Unlike for a 500 year return period, this would require relatively widespread financial aid schemes.

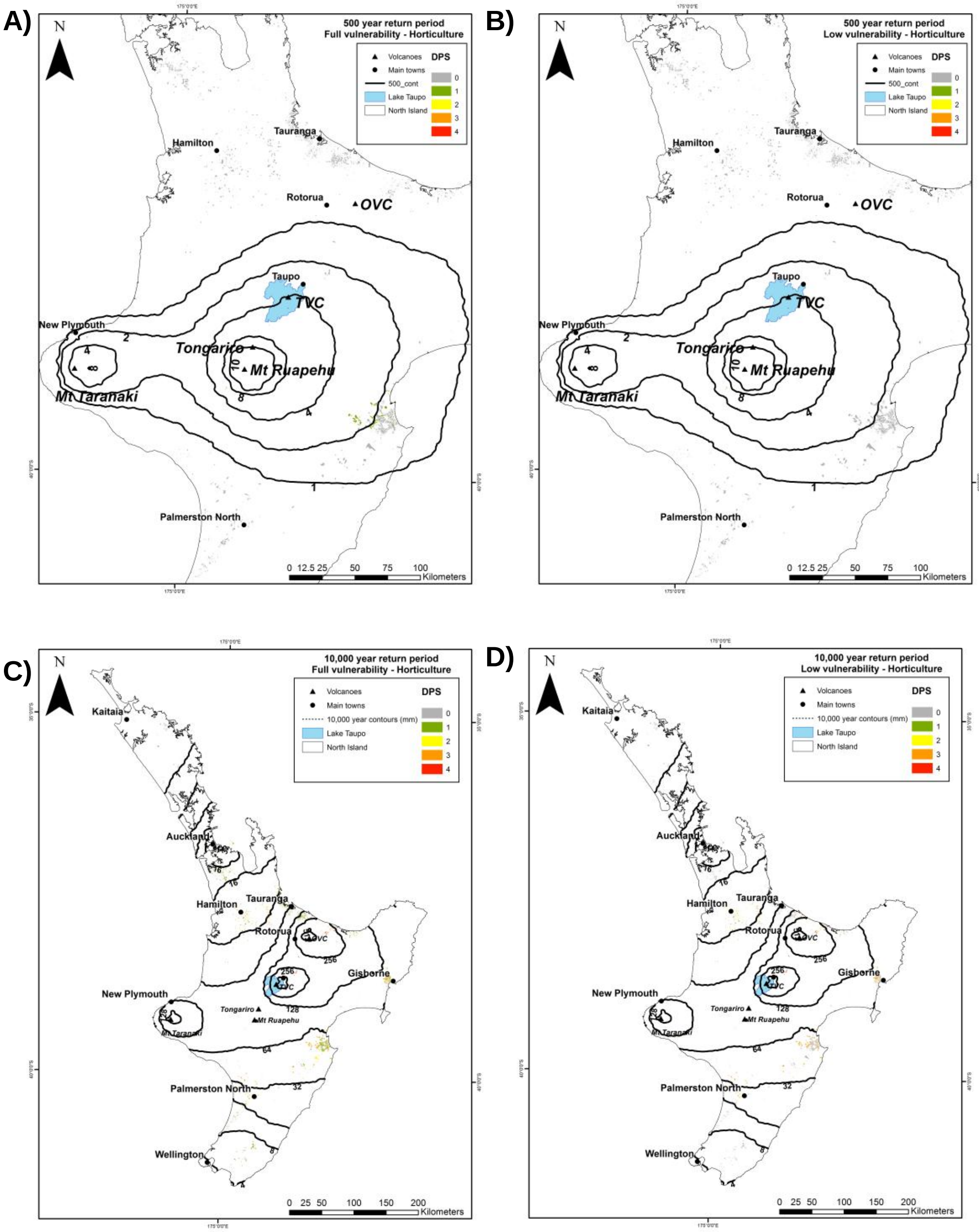


Figure 6.22: Impact assessment for horticultural farming systems due to tephra fall. A) DPS for a 500 year ARI tephra hazard surface at a time of full vulnerability; B) DPS for a 500 year ARI tephra hazard surface at a time of low vulnerability; C) DPS for a 10,000 year ARI tephra hazard surface at a time of full vulnerability; D) DPS for a 10,000 year ARI tephra hazard surface at a time of low vulnerability.

If a 10,000 year ARI tephra hazard surface is considered during a period of low vulnerability, the number of farms in DPS4 remains the same, but there is a decrease in the amount of horticulture within DPS2 and 3 (Fig. 6.22d). The number of farms that did not receive impacts (DPS0) is much greater with numbers ranging from 15.9% of leafy vegetables to 96.2% of tree fruits (Table 6.13). The different vulnerability levels of the horticultural sectors mean that if an eruption occurs during a period of low vulnerability some types of horticulture (e.g., tree fruits and root vegetables) may not require any management or financial assistance and efforts can be concentrated on less resilient farm types (e.g., viticulture and leafy vegetables).

6.4.2.3 Forestry

Impact assessments were also performed for North Island forestry. Forestry is much more resilient to tephra fall, compared to other types of agriculture. However, it does rely on harvesting machinery and road access in order to perform at full production levels (Sands 2005). A major challenge when assessing the possible impacts to forestry from a tephra fall is that the number of trees of each age group is not known (and is not quantified as part of the Agribase® dataset). This is important because if the plantings are seedlings they could be completely smothered by tephra fall, if the trees are young (less than 2 years old) then they are more likely to suffer structural breakages, and if the trees are harvestable (>10 years old) then harvesting machinery needs to be able to operate and road access is vital which can be challenging in a tephra fall environment (Neild et al. 1998). For the purposes of this assessment economic losses have been calculated based on the trees being harvestable. This means that it could be an overestimation of economic losses, however it is proposed here as a worse case scenario. When considering a 500 year ARI tephra hazard surface, only 2.5% of forestry falls in DPS1 (in the area around Mt. Ruapehu) with the rest remaining in DPS0 (Table 6.8; Fig. 6.23 a). DPS1 indicates that harvesting and access to the site would be compromised, rather than any damage to the trees. However, this could still have an impact if the trees are currently being removed, but it is unlikely that it would cause large, long-term financial losses.

A)

B)

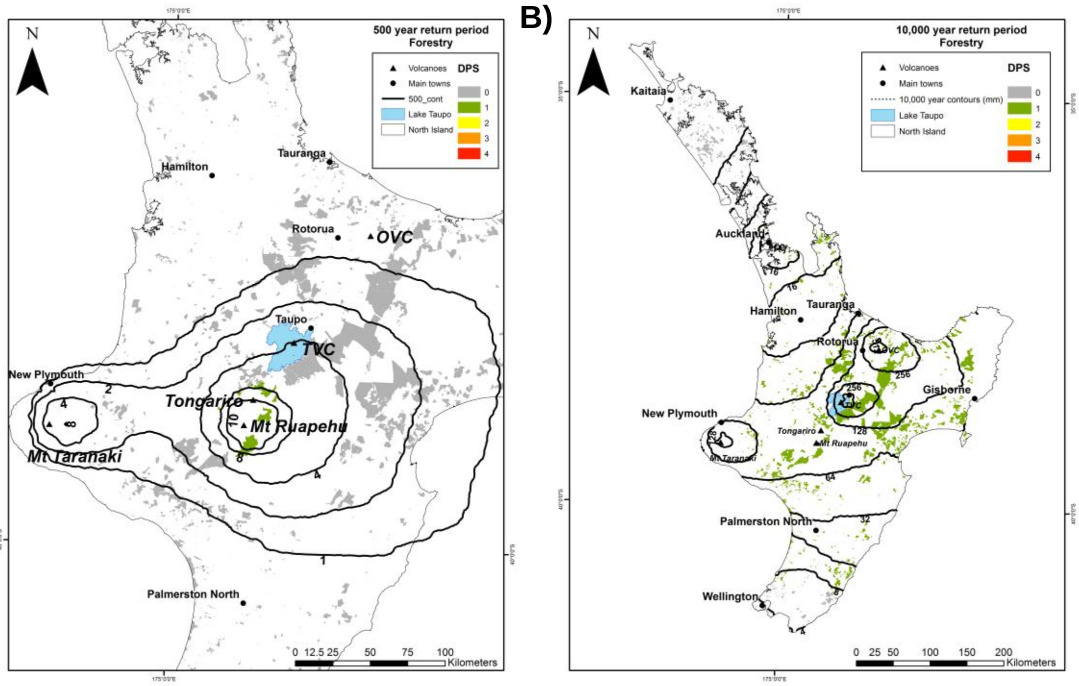


Figure 6.23: Impact assessment for forestry systems due to tephra fall. A) DPS for a 500 year ARI tephra hazard surface; B) DPS for a 10,000 year ARI tephra hazard surface.

More significant impacts to the forestry industry begin to occur when larger scale events are considered. When considering a 10,000 year ARI tephra hazard surface the close proximity of forestry land to active volcanoes becomes more apparent (Fig. 6.23 b). 85.2% of North Island forestry is classified as DPS1 after a 10,000 year event, likely due to accessibility and mechanical issues (Table 6.12). Whilst only 0.5% of forestry is categorised as DPS2 this represents a significant economic loss. If DPS2 is estimated to lower the production value of the affected trees by 10%, then economic losses could total ~$12 million (Table 6.9). Most of these losses will be due to tree breakages, damage to equipment, and lost time spent clearing tephra fall and re-opening access roads.

6.4.2.4 Greenhouses

A further impact assessment was undertaken for greenhouses, using the Maqsood et al. 2014 “large, commercial building” fragility curves as a proxy for the vulnerability of New Zealand greenhouses to tephra fall. A 500 year return period was trialled, however there was no impact to any North Island greenhouses because the only tephra fall deposits thick enough to cause damage were within the boundaries of Egmont National

Park (Taranaki) and Tongariro National Park where greenhouses are not permitted. Using a 10,000 year return period tephra fall the distribution of greenhouses within each damage index range was compiled as a count of individual structures and as a total area of greenhouse roof affected. Approximately 23% of greenhouses (or ~33% by area) suffer some damage due to the tephra fall event if dry, and ~30% (or ~ 41% by area) if wet (Table 6.15). Using a dry tephra scenario, 0.6% of greenhouses had a damage ratio of >0.8-1, this rose to 1.3% when considering a wet tephra deposit (Table 6.15). This means that the cost to repair the structure was greater than 80% of its total replacement value. This has implications for insurance, as owners need to ensure they are insured for the full replacement value of greenhouse structures, as even repairs could approach this amount.

Table 6.15: Number and total area of greenhouses impacted by damage index ranges using the 10,000 year ARI tephra hazard surface.

Return period			**10,000 year**	
Tephra			**Dry**	**Wet**
Damage Index	**0 (no damage)**	**Count**	543	498
		Count %	77.2	70.8
		Area (sq. m)	2261718	1986945
		Area %	67.5	59.3
	>0-0.2	**Count**	131	157
		Count %	18.6	22.3
		Area (sq. m)	987498	1075273
		Area %	29.5	32.1
	>0.2-0.4	**Count**	8	13
		Count %	1.1	1.8
		Area (sq. m)	66529	114710
		Area %	2.0	3.4
	>0.4-0.6	**Count**	16	11
		Count %	2.3	1.6
		Area (sq. m)	30017	82356
		Area %	0.9	2.5
	>0.6-0.8	**Count**	1	15
		Count %	0.1	2.1
		Area (sq. m)	1300	76852
		Area %	0.0	2.3
	>0.8-1	**Count**	4	9
		Count %	0.6	1.3
		Area (sq. m)	4060	14986
		Area %	0.1	0.4
Count			703	
Total area (sq. m)			3351122	

6.4.2.5 Deterministic Scenarios

The proposed fragility function suite was also applied to isopach maps of previous North Island tephra fall events. This allows the assessment of its applicability in scenario-based impact assessment, and comparisions between modelled and observed impacts in the case of the Ruapehu events.

<u>1995 Ruapehu eruption</u>

The 1995 Ruapehu eruption affected mostly pastoral land, where sheep were the dominant livestock type. The most notable agricultural impact of the event was the death of 2000 ewes on a large farm that received ~5 mm of tephra, due to suspected acute fluorosis (Johnston et al. 2000). The impact assessment was undertaken using the proposed fragility functions at a time of high vulnerability (as it would have been at the time of the eruption). The model does not predict animal deaths occurring, with damage to pastoral farms being confined to DPS1 (Fig. 6.24 a; Table 6.16 a). This is because the occurrence of fluorosis was likely due to animals already being exposed to access concentrations through the application of phosphatic fertilisers on pasture (Cronin et al. 2000). The inability to account for the pre-eruption exposure of livestock to fluoride when applying the fragility functions and fluoride coefficient is a limitation of the model.

Discounting the livestock deaths due to fluorosis the majority of farms received impacts that are relatively well represented by this impact assessment. Minor acid burns were seen in some forestry, however this did not affect productivity. Despite fears that the eruption would impact the fruit harvest there was no impact after the eruption. Cauliflower crops were affected with some farmers reporting lower production for the year (Johnston et al. 2000).

The impact assessment shows DPS distributions that lead to a similar description of impacts to those observed after the event. Economic costs of a 1995 Ruapehu eruption today are estimated by the model to be ~$1.5 million (Table 6.17 a). Dairy and pastoral farms are responsible for over $800,000 of the $1.4 million in losses, whereas forestry industry is modelled as suffering no overall economic losses (Table 6.17 a).

Unfortunately direct farm losses were not recorded after the 1995 or 1996 Ruapehu eruptions so no comparison can be made. Coordination costs for agricultural assistance from the Ministry of Agriculture (now the Ministry for Primary Industries) were ~\$382,500 (~\$560,600 in 2015) (Johnston et al. 2000). However, the relatively modest direct losses forecast by this model are consistent with reports from after the eruption - although workloads and anxiety did increase in rural communities suggesting that indirect losses may have been higher (Johnston et al. 1995). It is also important to note that land use change in the central North Island, predominantly from forestry to dairy farming has increased exposure and vulnerability to potential tephra fall losses.

1996 Ruapehu eruption

The June 1996 Ruapehu eruption effected the western part of the central North Island and was smaller than the 1995 events (Fig. 6.24 b). However, it was still a cause for concern for farmers in the affected area. Despite the smaller size, a greater percentage of agricultural land (0.2%) exceeded DPS0 than after the 1995 eruption (0.1%) (Table 6.16 b). This is due to the tephra deposit covering more agricultural land, whereas much of the thickest tephra deposits from the 1995 eruption were confined to the Tongariro National Park. Additionally, the 1996 eruption affected dairy farms to the north of Taupo (Fig. 6.24 b). Dairy farming is more vulnerable to tephra fall (than the sheep farming heavily impacted by the 1995 tephra fall), therefore a greater percentage of farms were in DPS1 (Table 6.16 b). Whilst a small number of dairy farms were effected by the 1996 tephra fall, as the number of dairy farms in the region has increased significantly in the 19 years since the eruption (Cameron & Bell 2008), it is expected that the impacts of a 1996 eruption would be more significant now. This is reflected in the economic losses estimated by the model based on current farm types and value (Table 6.17 b), where ~\$2.4 million in losses are predicted if a 1996 Ruapehu event occurred now. This is much greater than the losses that occurred in 1996 due to the increased amount of exposure and therefore losses that dairying receives (estimated at ~\$2.4 million; Table 6.17 b). These losses would be due to issues with milking machinery and refrigeration due to tephra contamination and possible power shortages, as well as problems transporting milk products across the central North Island.

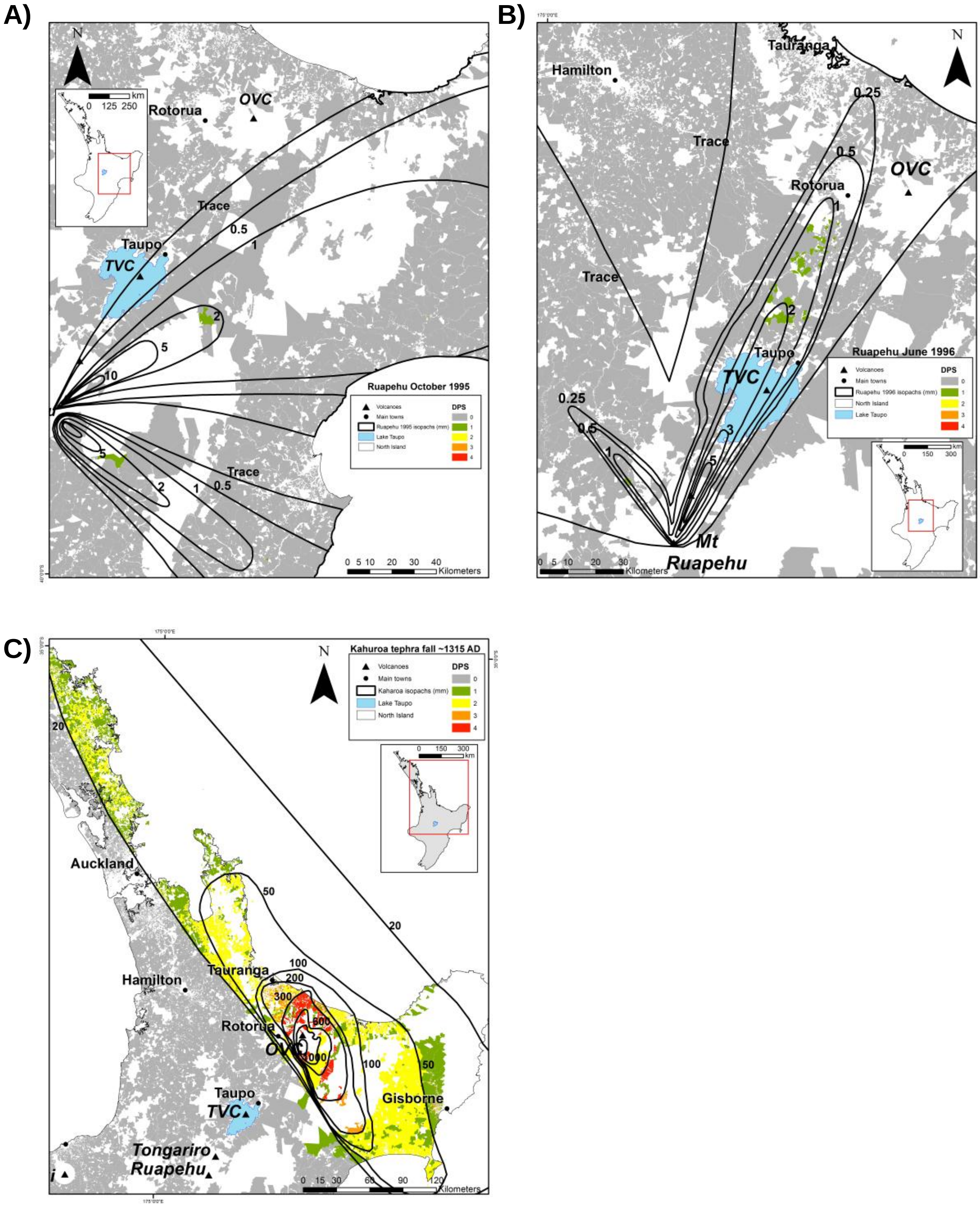


Figure 6.24: Impact assessment using deterministic scenarios. A) October 1995 Ruapehu eruptions; B) June 1996 Ruapehu eruptions; and C) ~1315 AD Kaharoa tephra fall.

Table 6.16: Land cover (ha) and percentage land (in the North Island) within each DPS at full vulnerability for the A) 1995 Ruapehu; B) 1996 Ruapehu; and C) ~1315 Kaharoa scenarios.

A) Agricultural sector	DPS0		DPS1		DPS2		DPS3		DPS4		Total Area (ha)
	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	
Cereals	82859.8	98.4	1311.7	1.6	0.0	-	0.0	-	0.0	-	84171.5
Fruit	3513.9	100.0	0.0	-	0.0	-	0.0	-	0.0	-	3513.9
Tree fruit	33768.3	100.0	0.0	-	0.0	-	0.0	-	0.0	-	33768.3
Root vegetables	11159.7	100.0	0.0	-	0.0	-	0.0	-	0.0	-	11159.7
Leafy vegetables	1971.7	98.1	37.5	1.9	0.0	-	0.0	-	0.0	-	2009.2
Viticulture	8171.2	86.6	1261.0	13.4	0.0	-	0.0	-	0.0	-	9432.2
Pastoral	5313930.0	99.9	3490.6	0.1	0.0	-	0.0	-	0.0	-	5317420.6
Dairying	1426149.2	99.8	2986.0	0.2	0.0	-	0.0	-	0.0	-	1429135.1
Forestry	1007363.5	100.0	10.0	0.0	0.0	-	0.0	-	0.0	-	1007373.5
Total Area (ha)	7888887.3	99.9	9096.8	0.1	0.0	0.0	0.0	0.0	0.0	0.0	7897984.1

B) Agricultural sector	DPS0		DPS1		DPS2		DPS3		DPS4		Total Area (ha)
	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	
Cereals	27808.8	99.5	130.8	0.5	0.0	-	0.0	-	0.0	-	27939.7
Fruit	3513.9	100.0	0.0	-	0.0	-	0.0	-	0.0	-	3513.9
Tree fruit	33763.5	100.0	4.7	0.0	0.0	-	0.0	-	0.0	-	33768.3
Root vegetables	11159.7	100.0	0.0	-	0.0	-	0.0	-	0.0	-	11159.7
Leafy vegetables	2009.2	100.0	0.0	-	0.0	-	0.0	-	0.0	-	2009.2
Viticulture	9420.8	99.9	11.4	0.1	0.0	-	0.0	-	0.0	-	9432.2
Pastoral	5317420.6	100.0	0.0	-	0.0	-	0.0	-	0.0	-	5317420.6
Dairying	1416198.7	99.1	12936.5	0.9	0.0	-	0.0	-	0.0	-	1429135.1
Forestry	1007373.5	100.0	0.0	-	0.0	-	0.0	-	0.0	-	1007373.5
Total Area (ha)	7828668.8	99.8	13083.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	7841752.3

C) Agricultural sector	DPS0		DPS1		DPS2		DPS3		DPS4		Total Area (ha)
	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	Area (ha)	Percentage	
Cereals	21133.9	75.6	0.0	-	0.0	-	4958.7	17.7	1847.0	6.6	27939.7
Fruit	1967.4	56.0	0.0	-	0.0	-	1104.0	31.4	442.6	12.6	3513.9
Tree fruit	13622.4	40.3	6119.6	18.1	7576.9	22.4	6449.3	19.1	0.0	-	33768.3
Root vegetables	10913.2	97.8	0.0	-	0.0	-	246.5	2.2	0.0	-	11159.7
Leafy vegetables	1418.6	70.6	0.0	-	544.0	27.1	0.0	-	46.6	2.3	2009.2
Viticulture	7824.5	83.0	0.0	-	0.0	-	1594.5	16.9	13.3	0.1	9432.2
Pastoral	4358477.6	82.0	384283.9	7.2	494916.0	9.3	38800.9	0.7	40942.2	0.8	5317420.6
Dairying	1072539.9	75.0	0.0	-	319263.7	22.3	0.0	-	37331.6	2.6	1429135.1
Forestry	632130.3	62.8	309606.0	30.7	65494.0	6.5	143.1	-	0.0	-	1007373.5
Total Area (ha)	6120027.8	78.0	700009.5	8.9	887794.6	11.3	53297.0	0.7	80623.3	1.0	7841752.3

Table 6.17: Tables estimating the potential financial losses (in NZD) in the first year for a A) October 1995 Ruapehu; B) June 1996 Ruapehu; and a C) ~1315 AD Kaharoa eruption.

A) 1995 Ruapehu		Cereals	Fruit	Tree fruit	Root vegetables	Leafy vegetables	Viticulture	Pastoral	Dairying	Forestry*
DPS	**Production per ha ($)**	1,000[a]	1,900[a]	4,400[a]	1,500[b]	3,500[c]	4,000[a]	800[a]	1,830[d]	25,000[e]
0	Area (ha)	82,859.8	3,513.9	33,768.3	11,159.7	1,971.7	8,171.2	5,313,930.0	1,426,149.2	1,007,363.5
	Approx % loss within DPS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
1	Area (ha)	1,311.7	0.0	0.0	0.0	37.5	1,261.0	3,490.6	2,986.0	10.0
	Approx % loss within DPS	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	0.0
	Approx $ losses	**131,170.0**	**0.0**	**0.0**	**0.0**	**13,141.0**	**504,406.6**	**279,249.7**	**546,429.7**	**0.0**
2	Area (ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx % loss within DPS	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	10.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0
3	Area (ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx % loss within DPS	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	50.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
4	Area (ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx % loss within DPS	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Total losses	**131,170.0**	**0.0**	**0.0**	**0.0**	**13,141.0**	**504,406.6**	**279,249.7**	**546,429.7**	**0.0**

Total losses for a 1995 Ruapehu event: ~$1.5 million

B) 1996 Ruapehu		**Cereals**	**Fruit**	**Tree fruit**	**Root vegetables**	**Leafy vegetables**	**Viticulture**	**Pastoral**	**Dairying**	**Forestry***
DPS	**Production per ha ($)**	1,000[a]	1,900[a]	4,400[a]	1,500[b]	3,500[c]	4,000[a]	800[a]	1,830[d]	25,000[e]
0	Area (ha)	27,808.8	3,513.9	33,763.5	11,159.7	2,009.2	9,420.8	5,317,420.6	1,416,198.7	1,007,373.5
	Approx % loss within DPS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
1	Area (ha)	130.8	0.0	4.7	0.0	0.0	11.4	0.0	12936.5	0.0
	Approx % loss within DPS	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	0.0
	Approx $ losses	**13,082.9**	**0.0**	**2,084.3**	**0.0**	**0.0**	**4,577.5**	**0.0**	**2,367,371.2**	**0.0**
2	Area (ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx % loss within DPS	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	10.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
3	Area (ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx % loss within DPS	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	50.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
4	Area (ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx % loss within DPS	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0
	Total losses	**$13,082.9**	**0.0**	**$2,084.3**	**0.0**	**0.0**	**$4,577.5**	**0.0**	**$2,367,371.2**	**0.0**

Total losses for a 1996 Ruapehu event: ~$2.4 million

C) ~1315 AD Kaharoa		Cereals	Fruit	Tree fruit	Root vegetables	Leafy vegetables	Viticulture	Pastoral	Dairying	Forestry*
DPS	**Production per ha ($)**	1,000[a]	1,900[a]	4,400[a]	1,500[b]	3,500[c]	4,000[a]	800[a]	1,830[d]	25,000[e]
0	Area (ha)	21,133.9	1,967.4	13,622.4	10,913.2	1,418.6	7,824.5	4,358,477.6	1,072,539.9	632,130.3
	Approx % loss within DPS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Approx $ losses	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
1	Area (ha)	0.0	0.0	6,119.6	0.0	0.0	0.0	384,283.9	0.0	309,606.0
	Approx % loss within DPS	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	0.0
	Approx $ losses	**0.0**	**0.0**	**2,692,618.0**	**0.0**	**0.0**	**0.0**	**30,742,713.5**	**0.0**	**0.0**
2	Area (ha)	0.0	0.0	7,576.9	0.0	544.0	0.0	494,916.0	319,263.7	65,494.0
	Approx % loss within DPS	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	10.0
	Approx $ losses	**0.0**	**0.0**	**9,092,279.5**	**0.0**	**571,172.8**	**0.0**	**118,779,842.8**	**175,275,772.2**	**163,735,049.9**
3	Area (ha)	4,958.7	1,104.0	6,449.3	246.5	0.0	1,594.5	38,800.9	0.0	143.1
	Approx % loss within DPS	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	50.0
	Approx $ losses	**2,975,207.0**	**1,258,554.3**	**17,026,280.6**	**221,835.6**	**0.0**	**3,826,799.1**	**18,624,435.4**	**0.0**	**157,110.1**
4	Area (ha)	1,847.0	442.6	0.0	0.0	46.6	13.3	40,942.2	37,331.6	0.0
	Approx % loss within DPS	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Approx $ losses	**1,847,048.8**	**840,925.5**	**0.0**	**0.0**	**163,274.2**	**53,021.6**	**32,753,776.4**	**68,316,792.2**	0.0
	Total losses	**$4,822,255.8**	**$2,099,479.8**	**$28,811,178.1**	**$221,835.6**	**$734,446.9**	**$3,879,820.7**	**$200,900,768.2**	**$243,592,564.4**	**$16,3892,160.0**

Total losses for a 1995 Ruapehu event: ~$650 million

*Forestry production per ha is for harvestable trees only.
a. ANZ 2013
b. Horticulture NZ 2013
c. Ministry of Primary Industries 2011
d. Dairy NZ 2013

~1315AD Kaharoa eruption

The ~1315 AD Kaharoa tephra fall event produced thickness greater than those predicted by the 10,000 year return period probabilistic hazard model (Hurst & Smith 2010) for the Bay of Plenty region. This demonstrates the low probability nature of the event, however it is important to consider due to the severe consequences such an event will cause. Whilst the impacts of the event on subsistence agricultural activity are not known, using the modern day farm distributions and types the likely impacts are severe. Around one percent of North Island agricultural land would require temporary abandonment for several months to years (DPS4), and a further 0.7% would require intensive mitigative measures (DPS3) (Table 6.16 c). The financial consequences would have a sizable effect on the New Zealand economy should an event such as this occur today. Based on current farm values and distributions a Kaharoa event is estimated to cause ~$649 million in losses at a time of high vulnerability (~$610 million at a time of low vulnerability), with the greatest economic losses to the dairying and pastoral sectors (both greater than $200 million; Table 6.17 c). It is also possible that these losses would be even greater as lower DPS (DPS1 and 2) are likely under represented by the assessment because the available isopach maps poorly constrain smaller thicknesses (<20 mm) due to a lack of deposit preservation. This means that if an event were to occur today it is likely that far more farms than shown in DPS1 and 2 (Fig. 6.24 c) would require supplementary feed and aid.

6.4.2.6 Overall discussion

The impacts to North Island agriculture from the tephra fall predicted from 500 year ARI tephra hazard surface, whilst disruptive on a local scale, are unlikely to cause long-term (>1-2 years) national level economic consequences. However, considering the tephra fall and impacts modelled based on a 10,000 year ARI tephra hazard surface, the social and economic consequences would be far-reaching and have a long term effect on national policy. Similarly, whilst the 1995 and 1996 Ruapehu eruption scenarios would be severe for those farms close to the volcano the event would likely be economically recoverable within a few years. However, a much larger tephra fall scenario such as the ~1315 AD Kaharoa event would have greater economic impacts for New Zealand.

The economic impacts to agriculture are highly dependent on the type of farming that is exposed, not only due to the difference in vulnerability but also the differences in the value of each farm type ($ per ha). The relative resilience of forestry to tephra fall impacts (Fig. 6.23), especially when compared to the vulnerable dairy sector (Fig. 6.20 & 6.21), is interesting in the current New Zealand agricultural context. The large number of conversions from forestry to the currently more profitable dairying in the central North Island (Landcare Research 2014), this means that overall North Island agriculture is becoming more vulnerable to tephra fall. Therefore, economic losses for future events will likely increase even if the tephra fall event is less severe.

Using the proposed fragility functions, agricultural impacts due to a specific tephra fall event can be estimated. This shows the application of this method as a predictive impact assessment tool to identify areas with different impact severities and target mitigation actions to appropriate locations. These could be used with forecasted models in the build up to an eruption, or after an eruption from field-mapped tephra thicknesses. Fragility function utility is demonstrated by the consistency between observed impacts after the 1995 and 1996 Ruapehu eruptions and the impacts predicted using the fragility functions.

6.5 Future applications and directions

The proposed suite of three damage state schemes (pastoral, horticulture and forestry) and the 13 new agricultural fragility functions were designed to be applicable to a variety of agricultural and volcanic settings. These tools can be used as the vulnerability input to perform an agricultural risk assessment, where the exposure and hazard information are also available. As the functions were developed using data from around the world and taking into account various methods and intensity of farming, it is possible that they could be used in most agricultural settings, however the limitations may vary dependent on location. The fragility functions here are generic curves that are not uniformly suitable for every agricultural environment. Where possible, the functions and vulnerability coefficients should be refined to more accurately capture the specific vulnerability of the target region. Additionally, the DPS and fragility functions could be used to model the impacts from a specific eruptive scenario. This could be useful as a decision-making tool at the early stages of an eruption when impacts have not fully manifested but management decisions are needed. The DPS schemes could also be adopted during post-event impact assessments to categorise observational impact information. This would also contribute to the impact dataset and the continued refinement of fragility functions.

The proposed fragility functions assess the overall production changes and damages that a particular farm would experience after a tephra fall. They do not explicitly include how impacts to specific interdependent systems, such as electricity or roading, would affect agricultural impacts. However, as they have been developed using data from previous case studies it is reasonable to assume that the overall impacts are capturing any losses caused by disruption to interdependent systems. As post-event impact assessments include more information on infrastructure impacts and the flow on effects that these may have for agricultural systems, it may be possible to refine the system of fragility functions to include different sets that show the different agricultural impacts with changes to the interdependent infrastructure (e.g., the impacts to a dairy farm when road closures impede milk tanker access, compared to those which remain accessible). However, using the currently available information any further categorising of data was not possible.

One of the major shortcomings of the proposed vulnerability tools is that they do not take into account the affect that immediate intervention and mitigation will have on the maximum impacts received. As more in depth post-event impact assessments are undertaken and a more quantitative dataset is established, a mitigation coefficient could be developed. This could be created using the same method used to calculate the seasonal and leachable fluoride coefficients for pastoral farming.

This study identified agricultural areas in the North Island of New Zealand that are at high risk of tephra fall impacts. Whilst this study does not provide recommendations to minimise these impacts through preparedness or mitigation strategies, the risk assessment could be used to provide targeted advice to high-risk areas or sectors. Future work could focus on using risk assessments to assist farmers and support agencies to develop mitigative strategies. Mitigation in high-risk areas could include changes in land use such as avoiding farming or undertaking less vulnerable forms of farming (e.g., root vegetables are less vulnerable than leafy vegetables); planning centralised access to management strategies that reduce impacts (e.g., cultivation machinery to combine tephra which soil, supplementary feed supplies for livestock, etc.); providing specific traning and technology transfer for farmers and agricultural managers in the best approaches for managing tephra impacts, preferably prior to a tephra fall event.

The use of the hazard surfaces produced by the Hurst & Smith (2010) PVHM, means that the modelling undertaken here is not a true risk assessment for a single event, rather a composite of all tephra producing events that the PVHM predicts will happen over the given ARI. An important next step is to apply the fragility function suite to individual simulations (single events from a specific vent within a given ARI) within a PVHM to produce a fully probabilistic risk assessment for that particular volcanic centre. This would be undertaken using the same methods used here for the derivation of impact data (DPS mapping) from the ARI tephra hazards surfaces and deterministic scenarios (Section 6.4.1).

6.6 Conclusions

This study presents a new set of DPS schemes and fragility functions derived from previous vulnerability studies and an extensive review of post-event impact assessments over the last 35 years. The fragility functions assess the probability of reaching or exceeding a DPS of between zero and four as a function of tephra thickness. The functions also take into account various vulnerability factors by considering agricultural type, size and intensity, as well as beginning to consider the affect that leachable chemistry will have on impacts.

Using the fragility functions developed in this study and a probabilistic tephra fall hazard model, an impact assessment is undertaken for North Island agriculture - demonstrating the practical use of the fragility functions suite. In quantifying the varying levels of vulnerabilities across a range of agricultural sectors, as well as factoring in seasonal and chemical influences, a thorough impact assessment was undertaken. Analysis of the economic outcomes indicated that the most costly losses will be in the pastoral and dairying sector, which is unsurprising as these make up the majority of North Island agriculture. Viticulture also presents a further area of high economic vulnerability. When considering smaller, more frequent events (i.e., a 500 year ARI tephra hazard surface) the main agricultural areas of concern are the dairying around Mt. Taranaki and to the east of Taupo, and pastoral farming around Mt. Ruapehu and the Tongariro National Park. It is possible that impacts in these areas could be reduced through enhanced risk awareness and reduction programmes, such as agricultural extension programmes, community based information sharing, evacuation and supplementary feed coordination planning, and preparedness exercises. When considering more infrequent, high consequence events (i.e., a 10,000 year ARI tephra hazard surface) a much broader range of agricultural types would be impacted. This type of event will present a massive management challenge and will likely result in hundreds of millions to billions of dollars of agricultural production loss. However, undertaking risk assessments can assist emergency management and response by classifying farms into DPS, which can allow for targeted aid and rehabilitation planning.

6.7 Acknowledgments

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6.8 References

Araya, O., Wittwer, F., Villa, A., & Ducom, C. (1990). Bovine fluorosis following volcanic activity in the southern Andes. Veterinary Record, 126(26), 641–642. Retrieved from http://www.cabdirect.org/abstracts/19902210133.html

Arteca, R. N. (2015). Introduction to horticultural science (Second Ed.). Cengage Learning, Stamford.

Aspinall, W. P. (2006). Structured Elicitation of Expert Judgment for Probabilistic Hazard and Risk Assessment in Volcanic Eruptions. In H. M. Mader, S. G. Coles, C. B. Connor, & L. J. Connor (Eds.), Statistics in volcanology (pp. 15–30). Special publication of IAVCEI; Geological Society, London.

AssureQuality. (2014). AgriBase agricultural dataset.

Baker, J. (2014). Efficient analytical fragility function fitting using dynamic structural analysis. Earthquake Spectra, In press. Retrieved from http://earthquakespectra.org/doi/abs/10.1193/021113EQS025M

Bargle, C., Williams, C., & Croy, D. (2013). New Zealand economics: ANZ agri-focus. Wellington.

Barnard, S. T. (2003). Potential physical effects of any future 1886-type eruption from Tarawera volcano on the Bay of Plenty area. MSc. Thesis, University of Canterbury.

Birot, Y., & Gollier, C. (2001). Risk assessment, management and sharing in forestry, with special emphasis on wind storms. In 14th Convocation of Academies of Engineering and Technological Sciences (pp. 1–16). Espoo, Finland. http://doi.org/10.1152/ajpcell.00303.2005

Blong, R. (2003). A Review of Damage Intensity Scales. Natural Hazards, 29, 57–76.
Cameron, M. P., & Bell, K. (2008). New Zealand dairying in the Waikato region of New Zealand: an overview of historical statistics. Hamilton. Retrieved from http://researchcommons.waikato.ac.nz/handle/10289/1585

Carmel, Y., Paz, S., Jahashan, F., & Shoshany, M. (2009). Assessing fire risk using Monte Carlo simulations of fire spread. Forest Ecology and Management, 257(1), 370–377. http://doi.org/10.1016/j.foreco.2008.09.039

Chuvieco, E., Aguado, I., Yebra, M., Nieto, H., Salas, J., Martín, M. P., Vilar, L., Martinez, J., Martin, S., Ibarra, P., de la Riva, J., Baeza, J., Rodriguez, F., Molina, J. R., Herrera, M. A., & Zamora, R. (2010). Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. Ecological Modelling, 221(1), 46–58. http://doi.org/10.1016/j.ecolmodel.2008.11.017

Cook, R. J., Barron, J. C., Papendick, R. I., & Williams, G. J. (1981). Impact on agriculture of the Mount St. Helens eruptions. Science (New York, N.Y.), 211(4477), 16–22. http://doi.org/10.1126/science.211.4477.16

Cronin, S. J., Hedley, M. J., Neall, V. E., & Smith, R. G. (1998). Agronomic impact of tephra fallout from the 1995 and 1996 Ruapehu Volcano eruptions , New Zealand. Environmental Geology, 34(April), 21–30.

Cronin, S. J., Manoharan, V., Hedley, M. J., & Lognathan, P. (2000). Fluoride: A review of its fate, bioavailability, and risks of fluorosis in grazed - pasture systems in New Zealand. New Zealand Journal of Agricultural Research, 43(3), 295–321.

Cronin, S. J., Neall, V. E., Lecointre, J. A., Hedley, M. J., & Loganathan, P. (2003). Environmental hazards of Fluoride in volcanic ash : a case study from Ruapehu volcano, New Zealand. Journal of Volcanology and Geothermal Research, 121, 271-291.

DairyNZ Limited. (2014). DairyNZ Economic Survey 2012-13. Hamilton.

Drouineau, S., Laroussinie, O., Birot, Y., Terrasson, D., Formery, T., & Roman-Amat, B. (2000). Joint Evaluation of Storms, Forest Vulnerability and their Restoration. Discussion Paper - European Forest Institute (EFI).

Finney, M. A. (2004). FARSITE : Fire Area Development and Evaluation. United States Department of Agriculture, Research paper RMRS-RP-4 Revised. 52pp.

Finney, M. A. (2005). The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management, 211(1-2), 97–108. http://doi.org/10.1016/j.foreco.2005.02.010

Flueck, W. T. (2013). Effects of fluoride intoxication on teeth of livestock due to a recent volcanic eruption in eruption in Patagonia, Argentina. Online Journal of Veterinary Research, 17(4), 167–176.

Gardiner, B. A., & Quine, C. P. (2000). Management of forests to reduce the risk of abiotic damage - A review with particular reference to the effects of strong winds. Forest Ecology and Management, 135(1-3), 261–277. http://doi.org/10.1016/S0378-1127(00)00285-1

Hardy, C. C. (2005). Wildland fire hazard and risk: Problems, definitions, and context. Forest Ecology and Management, 211(1-2), 73–82. http://doi.org/10.1016/j.foreco.2005.01.029

Hurst, A. W. (1994). Estimating Fallout ASHFALL – A Computer Program for Estimating Volcanic Ash Fallout Report and Users Guide. Institute of Geological & Nuclear Sciences science report 94/23.

Hurst, T., & Smith, W. (2004). A Monte Carlo methodology for modelling ashfall hazards. Journal of Volcanology and Geothermal Research, 138(3-4), 393–403. http://doi.org/10.1016/j.jvolgeores.2004.08.001

Hurst, T., & Smith, W. (2010). Volcanic ashfall in New Zealand – probabilistic hazard modelling for multiple sources. New Zealand Journal of Geology and Geophysics, 53(1), 1–14. http://doi.org/10.1080/00288301003631129

ISDR. (2009). 2009 UNISDR Terminology on Disaster Risk Reduction. Geneva, Switzerland.

Jenkins, S. F., & Spence, R. J. S. (2009). Vulnerability curves for buildings and agriculture. FP7-MIAVITA Delieverable-D4.b. 66pp.

Jenkins, S. F., Spence, R. J. S., Fonseca, J. F. B. D., Solidum, R. U., & Wilson, T. M. (2014). Volcanic risk assessment: Quantifying physical vulnerability in the built environment. Journal of Volcanology and Geothermal Research, 276, 105–120. http://doi.org/10.1016/j.jvolgeores.2014.03.002

Jenkins, S. F., Wilson, T. M., Magill, C. R., Miller, V., & Stewart, C. (2014). Volcanic ash fall hazard and risk: Technical background paper for the UN-ISDR Global Assessment Report on Disaster Risk Reduction 2015. Retrieved from http://muse.jhu.edu/content/crossref/journals/mln/v120/120.3contributors.html

Johnston, C., & Jeunemaitre, A. (2011). Risk and the role of scientific input for contingency planning: a response to the April 2010 Eyjafjallajokull volcano eruption. In A. Alemanno (Ed.), Governing disasters: the challenges of emergency risk regulation (pp. 51–65). Massachusetts: Edward Elgar Publishing.

Johnston, D. M. (1997). Physical and social impacts of past and future volcanic eruptions in New Zealand. PhD. Thesis, Massey University.

Johnston, D. M., Houghton, B. F., Neall, V. E., Ronan, K. R., & Paton, D. (2000). Impacts of the 1945 and 1995-1996 Ruapehu eruptions, New Zealand: An example of increasing societal vulnerability. Geological Society of America Bulletin, (5), 720–726.

Johnston, D. M., Ronan, K. R. and Houghton, B. F. (1995). The Physical and Social Impacts of the 1995 Ruapehu Eruption. New Zealand: An Overview, Vancouver.

Kaye, G. (2008). Volcanic hazard risk assessment for the RiskScape program, with test application in Rotorua, New Zealand, and Mammoth Lakes, USA. University of Canterbury. Retrieved from http://www.ir.canterbury.ac.nz/handle/10092/1950

Landcare Research. (2014). LCDB v4.0 - Land cover database version 4.0.

LINZ. (2015). NZ building polygons (Topo, 1:50k).

Livesey, C., & Payne, J. (2011). Diagnosis and investigation of fluorosis in livestock and horses. In Practice, 33(9), 454–461. http://doi.org/10.1136/inp.d6078

Maqsood, T., Wehner, M., Ryu, H., Edwards, M., Dale, K., & Miller, V. (2014). GAR15 regional vulnerability functions. In UNISDR/GA SE Asian Regional Workshop on Structural Vulnerability Models for the GAR Global Risk Assessment, 11-14 November, 2013 (pp. 1–606). Canberra, Australia: Geoscience Australia. Record 2014/38.

Matthews, P. N. P., Harrington, K. C., & Hampton, J. G. (1999). Livestock farming systems in New Zealand. In J. White & J. Hodgson (Eds.), New Zealand crop and pasture science (pp. 133–152). Auckland: Oxford University Press.

McDonald, P., Edwards, R. A., Greenhalgh, J. F. D., Morgan, C. A., Sinclair, L. A., & Wilkinson, R. G. (2011). Animal nutrition (Seventh Ed). Essex, England: Prentice Hall.

Ministry of Agriculture and Forestry. (2010). 2009 Horticulture and arable monitoring process and fresh vegetables. Wellington.

Neild, J., Flaherty, P. O., Hedley, P., Underwood, R., Johnston, D., Christenson, B., & Brown, P. (1998). Impact of a Volcanic Eruption on Agriculture and Forestry in New Zealand. MAF policy technical paper 99/2. 92pp.

Pevreal, C. W. (2007). Volcanic impact to viticulture in the Hawke's Bay. BSc. Hons. Dissertation, University of Canterbury.

Porter, K., Kennedy, R., & Bachman, R. (2007). Creating fragility functions for performance-based earthquake engineering. Earthquake Spectra, 23(2), 471–489. http://doi.org/10.1193/1.2720892

Reese, S., Bradley, B. a., Bind, J., Smart, G., Power, W., & Sturman, J. (2011). Empirical building fragilities from observed damage in the 2009 South Pacific tsunami.

Earth-Science Reviews, 107(1-2), 156–173.
http://doi.org/10.1016/j.earscirev.2011.01.009

Reese, S., & Ramsay, D. (2010). Riskscape: Flood fragility methodologies. Wellington.
Rossetto, T., Ioannou, I., & Grant, D. N. (2013). Existing Empirical Fragility and Vulnerability Relationships: Compendium and Guide for Selection, Pavia, Italy.

Rossetto, T., Ioannou, I., Grant, D. N., & Maqsood, T. (2014). Guidelines for Empirical Vulnerability Assessment Report produced in the context of the Vulnerability Global Component project, Pavia, Italy.

Rubin, C. H., Noji, E. K., Seligman, P. J., Holtz, J. L., Grande, J., & Vittani, F. (1994). Evaluating a fluorosis hazard after a volcanic eruption. Archives of Environmental Health, 49(5), 395–401. http://doi.org/10.1080/00039896.1994.9954992
Sahetapy-Engel, S., Self, S., Carey, R. J., & Nairn, I. A. (2014). Deposition and generation of multiple widespread fall units from the c. AD 1314 Kaharoa rhyolitic eruption, Tarawera, New Zealand. Bulletin of Volcanology, 76(8), 836-864. http://doi.org/10.1007/s00445-014-0836-4

Sands, R. (2005). Forestry in a global context. Wallingford: CABI International.

Sparks, R. J., Aspinall, W. P., Crosweller, H. S., & Hincks, T. K. (2013). Risk and uncertainty assessment of volcanic hazards. In Risk and uncertainty assessment for natural hazards (p. 558). Cambridge: Cambridge University Press.

Spence, R., Gunesekara, R., & Zuccaro, G. (2009). Insurance risks from volcanic eruptions in Europe. Willis Research Network, WRN research bulletin.

Sword-Daniels, V., Wardman, J., Stewart, C., Wilson, T., Johnston, D., & Rossetto, T. (2011). Infrastructure impacts, management and adaptations to eruptions at Volcán Tungurahua, Ecuador, 1999-2010.

Tarbotton, C., Dall'Osso, F., Dominey-Howes, D., & Goff, J. (2015b). The use of empirical vulnerability functions to assess the response of buildings to tsunami impact: Comparative review and summary of best practice. Earth-Science Reviews, 142, 120–134. http://doi.org/10.1016/j.earscirev.2015.01.002

The New Zealand Institute for Plant and Food Research. (2013). Fresh Facts 2013. Annual Industry Summary. Auckland.

Trujillo, M., Baas, S., Ricoy, A., Battista, F., Herold, J., & Vantwout, T. (2014). Mainstreaming disaster risk reduction in agriculture: An assessment of progress made against the Hyogo framwork for action. Input paper for the Global Assessment Report on DRR. 94pp.

Uma, S. R., Dhakal, R. P., & Nayyerloo, M. (2013). Vulnerability assessment of christchurch buildings in Canterbury earthquakes. GNS Science report 2013/20. 39pp.

UNISDR (2015). Sendai Framework for Disaster Risk Reduction 2015 - 2030.

Vadrevu, K. P., Eaturu, A., & Badarinath, K. V. S. (2010). Fire risk evaluation using multicriteria analysis-a case study. Environmental Monitoring and Assessment, 166(1-4), 223–239. http://doi.org/10.1007/s10661-009-0997-3

Wardman, J. B., Wilson, T. M., Bodger, P. S., Cole, J. W., & Stewart, C. (2012). Potential impacts from tephra fall to electric power systems: a review and mitigation strategies. Bulletin of Volcanology, 74(10), 2221–2241. http://doi.org/10.1007/s00445-012-0664-3

Weinstein, H., & Davidson, A. (2004). Fluorides in the environment: effects on plants and animals. Cambridge, MA.

White, J., & Hodgson, J. (1999). New Zealand pasture and crop science. Auckland: Oxford University Press.

Whitman, Z. (2014). Rural organisational impacts, responses, and recoveries to natural disasters: Case studies from the Canterbury Earthquake Sequence and the 2010 Southland snowstorm. PhD. Thesis, University of Canterbury.

Wilson, G., Wilson, T. M., Deligne, N. I., & Cole, J. W. (2014). Volcanic hazard impacts to critical infrastructure: A review. Journal of Volcanology and Geothermal Research, 286, 148–182. http://doi.org/10.1016/j.jvolgeores.2014.08.030

Wilson, T., Cole, J., Cronin, S., Stewart, C., & Johnston, D. (2011). Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: lessons for recovery. Natural Hazards, 57(2), 185–212. http://doi.org/10.1007/s11069-010-9604-8

Wilson, T., Dantas, A., & Cole, J. (2009). Modelling livestock evacuation following a volcanic eruption: An example from Taranaki volcano, New Zealand. New Zealand Journal of Agricultural Research, 52(1), 99–110. http://doi.org/10.1080/00288230909510493

Wilson, T., & Kaye, G. (2007). Agricultural fragility estimates for volcanic ash fall hazards. GNS Science Report 2007/37. 52pp.

Wilson, T., Kaye, G., Stewart, C., & Cole, J. (2007). Impacts of the 2006 eruption of Merapi volcano, Indonesia, on agriculture and infrastructure. GNS Science report 2007/07. 71pp.

Wilson, T. M., & Cole, J. W. (2007). Potential impact of ash eruptions on dairy farms from a study of the effects on a farm in eastern Bay of Plenty, New Zealand; implications for hazard mitigation. Natural Hazards, 43(1), 103–128. http://doi.org/10.1007/s11069-007-9111-8

Wilson, T. M., Stewart, C., Sword-Daniels, V., Leonard, G. S., Johnston, D. M., Cole, J. W., Wardman, J., Wilson, G., & Barnard, S. T. (2012). Volcanic ash impacts on critical infrastructure. Physics and Chemistry of the Earth, Parts A/B/C, 45-46, 5–23. http://doi.org/10.1016/j.pce.2011.06.006

Chapter Seven
Conclusions and future research

7.1 Thesis overview

The aim of this thesis was to investigate how vulnerability characteristics (VC) influence tephra fall impacts to agriculture. The research is undertaken on the basis that accurate, robust risk assessments are required to inform effective disaster risk management and are vital in promoting disaster risk reduction (DRR). Previous observational impact assessment data, and qualitative vulnerability information were used to create risk assessment tools. This thesis improves the understanding of agricultural vulnerability to tephra fall in a number of key aspects.

These aspects were addressed through the following thesis components:

1. A comprehensive post-event impact assessment (Post-EIA) after the 2011 Cordón Caulle – Volcanic Complex (CC-VC) tephra fall event (Appendix D), and the correlation of the observed impacts to previous hazard intensity thresholds (tephra thicknesses) and impact descriptors (Chapter 2). This work informed the creation of post-event impact assessment guidelines for agriculture, and tested the applicability of tephra thickness thresholds for impacts proposed by Jenkins et al. 2014, and Wilson et al. 2014.
2. The assessment of the toxicity risk to agricultural systems due to environmentally-available elements introduced by the 2011 CC-VC tephra fall (Chapter 3). This demonstrates the importance of undertaking robust hazard and vulnerability assessments after a tephra fall to accurately understand the ways that the impacts manifest themselves, which can inform targeted mitigation and recovery strategies.
3. A comparison of the agricultural impacts, and associated management strategies and vulnerability characteristics after the 1991 Hudson, 2008 Chaitén, and 2011 CC-VC tephra fall events (Chapter 4). From these studies trends in the farm

properties that influenced vulnerability to tephra fall impacts were identified. These included the climatic zone of the farm, the type, size and intensity of farming, and the accessibility of 'improvement' assets such as irrigation and cultivation machinery.

4. The development of an agricultural impacts database (AID) and a set of post-event impact assessment questions that will allow for the completion of an AID entry (Chapter 5). This is important, as it will encourage the standardisation of post-EIA data both in its collection, and compilation. It will also ensure that the most useful information about agricultural impacts and their causes are being recorded, so that the data needs required to refine predictive models and the risk assessment tools are met.
5. The creation of a set of three damage/production state (DPS) schemes (for pastoral and horticultural farming, and forestry). These provide a quantitative scale (each level with qualitative descriptors) to measure and classify agricultural impacts. These were then used to create a suite of agricultural fragility functions which show the probability of reaching a particular DPS at a given tephra thickness (Chapter 6). These are unique in that they include 14 sets of functions for various farm types and intensities, as well as including a seasonal and fluoride coefficient to modify the vulnerability dependent on the time the eruption occurs in and the environmentally-available level of fluoride.
6. The application of the fragility function suite to 500 and 10,000 annual recurrance interval hazard surfaces for New Zealand, and three deterministic scenarios (1995 and 1996 Ruapehu and ~1315 Kaharoa tephra falls) (Chapter 6). This demonstrates the use of the fragility functions in risk and impact assessments both pre- and post- event.

7.2 Research outcomes

This thesis investigates the relationship between agricultural impacts from tephra fall and the hazard and vulnerability factors that influence these impacts. This research was undertaken in order to provide a framework for the assessment and prediction of agriculture impacts, which will inform and facilitate targeted DRR efforts.

Increasing tephra thicknesses are commonly attributed to causing more severe agricultural impacts; however, by examining, in detail, the information from case studies in Chapters 2, 3, and 4 (and Appendix D), additional sources of vulnerability that influence impacts to agricultural systems were identified. These vulnerability characteristics (VC) are fundamental to understanding impacts to agriculture, and the development of assessment tools that better anticipate impact mechanisms and occurrence. Drawing upon the lessons from this research, the following tools, which contribute to tephra fall vulnerability analysis, and thus risk assessment for agriculture were developed:

- DPS schemes for pastoral and horticultural farming, and forestry to quantify impact information and classify the impacts forecasted by fragility functions.
- Fragility functions which quantify the probability of each DPS occurring at a given tephra thickness.
- Guidelines for suggested site visits and interview questions for post-EIA of agricultural areas after a tephra fall event.
- A proposed agricultural impacts database (AID) for the collation of post-EIA data.

These tools are intrinsically linked as they inform each other and the refinement of each is dependent on the information provided by the rest of the framework. For example, the guidelines for post-EIA techniques (Chapter 5) were developed specifically to facilitate the collection of data, which allows for the refinement of the fragility functions in Chapter 6. Equally, in developing the fragility functions, a range of information needs were identified and incorporated into the impact assessment guidelines and AID in order to ensure their capture within the database. Additionally, DPS categories were divided based on the groupings of impacts observed after previous events (specifically the Hudson, Chaitén, and CC-VC tephra falls) rather than arbitrarily. This holistic approach facilitates the continued addition of impact (and associated hazard and vulnerability) data, the refinement of tools, and the improvement of agriculture risk assessment.

The main contribution of this research and the assessment tools is the advancement of quantitative agricultural vulnerability and risk assessment for tephra fall hazards. When considering tephra fall, there have been numerous quantitative tephra fall hazard models and tools developed (e.g., Bonadonna et al. 2005; Hurst 1994), however quantitative vulnerability methods for exposed sectors (and thus risk models) are less well developed. In order to perform robust volcanic risk assessments both the hazard and vulnerability information needs to be accurately quantified, the imbalance of information in favour of hazard data means that volcanic risk models are likely imprecise. The thesis addresses this for agriculture by systematically deriving a suite of fragility functions for agricultural systems which quantitatively estimate agriculture vulnerability and impacts for tephra fall hazards. These functions represent a first attempt at the creation of fragility functions for agricultural systems impacted by tephra fall. The functions derived are an improvement on previous studies, because they incorporate farming intensity (proxy for climate), and farm size (related to available farm assets) into the fragility functions suite, as well as the timing of the tephra fall (seasonality) and tephra-sourced fluoride concentrations through the modification of functions by specific coefficients. As discussed in Chapter 6 (Section 6.4), these functions can be used for risk assessment using probabilistic hazard models, or in impact assessments to assess the effect that a certain scenario would have on exposed agriculture. These assessments could be undertaken in any location where: 1) there is an available probabilistic or deterministic tephra hazard model; 2) access to exposure information such as type and location of affected farms; and 3) there are fragility functions available for the affected farm types.

Understanding and mitigating against risk by developing policy and field methods is a priority of the United Nations International Strategy for Disaster Reduction, outlined in the Sendai Framework (UNISDR 2015). Fragility functions, such as those presented in Chapter 6, can be used to identify areas of high risk and allow optimised risk reduction measures to be implemented (e.g., land-use planning and government policy changes, structural shifts to farming types and methods for these areas, etc.). By performing risk assessments using a quantitative approach, cost-benefit analysis can also be undertaken to prioritise mitigation options and ensure that these options are economically viable.

Additionally, the functions can be used in a deterministic manner to investigate a particular hazard scenario either before an eruption (e.g. during an emergency management planning exercise) or during an eruption crisis to assess the likely impacts of a tephra fall before they fully manifest, to inform and support emergency management and response planning.

An additional aim of this research was to allow for the incorporation of future research into the risk assessment framework. Using the post-EIA guidelines and the proposed AID, it is hoped that the dataset will continue to expand, which will lead to progressive refinement of fragility functions. In turn this will increase the accuracy of agriculture risk assessments leading to more effective DRR.

7.3 Future research directions

Future research should focus on the refinement of predictive models (such as fragility functions) as agricultural vulnerability quantification is improved through greater quantity and quality of impact data collection by more consistent post-EIA and other empirical methods. This will lead to a more holistic understanding of agricultural impacts and the hazard and vulnerability characteristics that determine their severity, allowing for targeted preparedness and mitigative strategies.

7.3.1 Refining fragility functions

The proposed fragility functions represent a first attempt at the creation of fragility functions for agricultural systems after tephra fall. Previous work (notably Wilson & Kaye 2007) has focused on the creation of vulnerability functions that show the damage ratio or percentage production losses due to tephra thickness. In contrast, this research utilised the DPS schemes and incorporated uncertainty through the use of probability curves for each DPS, rather than a single vulnerability curve. However, there are a number of limitations and assumptions made, which can be refined with future research.

The tephra thicknesses used to create the fragility functions were taken from the total tephra thickness recorded at a particular site. As the data points came from various sources it is assumed that these were taken at the end of a particular eruptive sequence and represent the entirety of the fall thickness. Realistically it is likely that these comprised various individual tephra fall events and is therefore a cumulative thickness, which is not taken into account in this study. Future work could focus on how multiple tephra fall events (and the timing of these) will affect agricultural impacts. Long-lasting eruption sequences should also be considered, as it is likely that these would cause cumulative impacts as vulnerability to tephra fall increases as the eruptions continue.

An aspect of agricultural impacts that is still poorly defined by the proposed tools is the temporal evolution of impacts. Impacts such as production loss, vegetation damage, and adverse animal health consequences, will not manifest instantly after a tephra fall event. Instead impacts may take months to occur and even longer to be accurately recorded. The proposed fragility functions show the probability of the DPS at the time of maximum impact, however this may vary between events. As more specific post-EIA information becomes available, the timing of losses could be better understood and incorporated into management and response planning.

Additionally, the nature of agricultural impacts means that it is possible that mitigative actions immediately after a tephra fall event may alter the maximum impact at the given tephra thickness had no intervention occurred. These actions include tephra removal, cultivation of the tephra into the topsoil, irrigation, and re-seeding of pasture and crops (Wilson et al. 2009). Whilst this mitigative influence is difficult to measure and represent, it would aid in response decision-making. The difference a particular action is going to have on the severity of impacts could then be assessed against the time and monetary cost of the action. This ‘mitigation decay function’ or coefficient could be incorporated into fragility functions in numerous ways (Fig. 7.1). However, further investigation of case studies that include detailed descriptions of the mitigation actions undertaken and the resultant change in impacts are needed. Ideally this would include the change in impacts and mitigation with multiple tephra fall events. However, this would require a series of impact assessments after each tephra fall event in the same sites. These impact assessments would need precise information on the mitigation measures that have been employed between each tephra fall event, and the influence that these have had on the systems recovery.

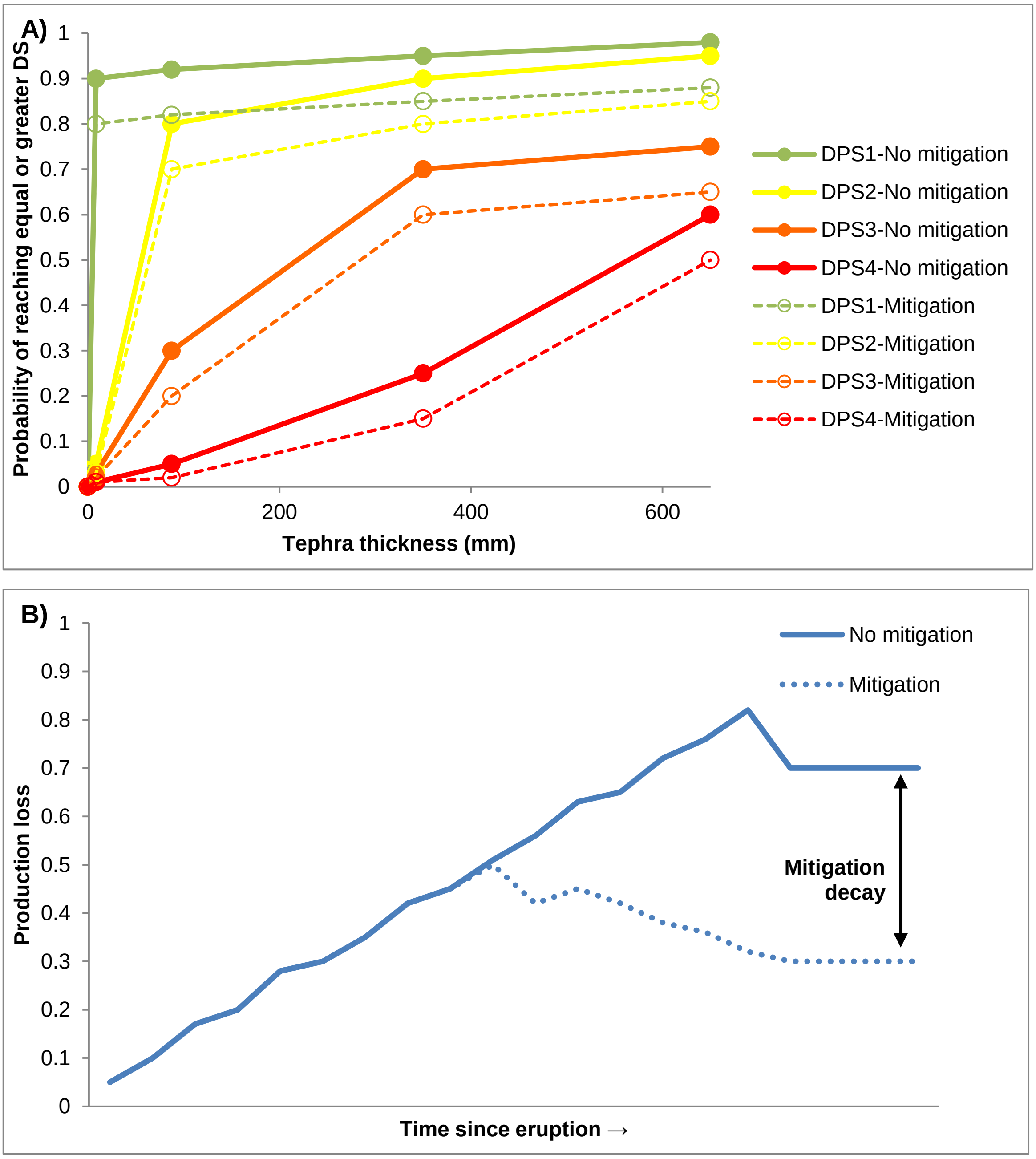

Figure 7.1: Graphs demonstrating possible methods of quantifying the effect that mitigation techniques have on agricultural impacts - A) The calculation of a mitigation coefficient that can be applied to the DPS probabilities in the fragility functions; and B) the difference in the change in production impacts over time with mitigation and without, could allow for the calculation of a mitigation decay function.

This thesis found that the climatic zone within which the agricultural area is situated and precipitation have a large influence on the impacts that occur, independent of the tephra fall characteristics (Chapters 2, 3, & 4). For the purposes of this study, the intensity of farming was presumed to be a relatively reliable proxy for climate (i.e., low intensity farming often occurs in semi-arid to arid zones; high intensity farming is typically located in temperate regions). This distinction was necessary because of the small number of data points available. However, future work using an expanded number of case studies, and possibly field experiments could better constrain fragility functions dependent on precipitation levels.

Quantifying the relationship between tephra remobilisation and precipitation levels is important due to the severe negative impacts that wind remobilisation and lahars can have on agricultural areas (Mercado et al. 1996; Wilson et al. 2011). Any numeric relationships would depend on the exact environmental conditions, and the physical properties of the tephra deposit. Additionally, access to cultivation and irrigation which can modify the deposit's incorporation into the soil, further complicates any relationship. However, the development of a generic model could aid in forecasting high spatial and temporal risk, which in turn could allow for preparedness planning and targeted DRR strategies. Figure 7.2 demonstrates a possible relationship, where thresholds are placed on wind and lahar remobilisation.

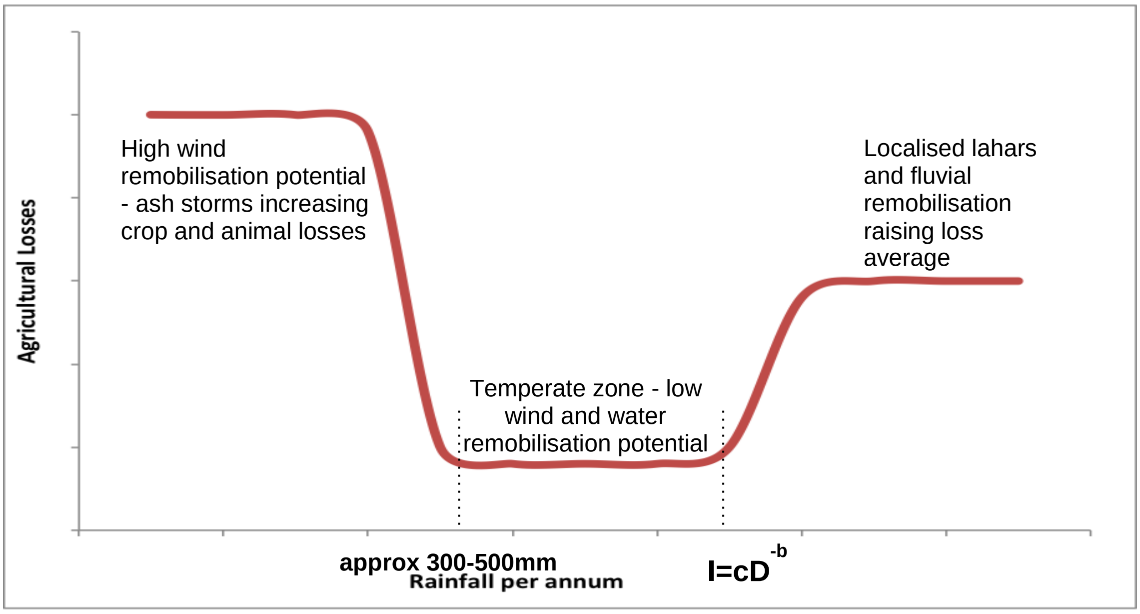

Figure 7.2: Possible theoretical model of precipitation effects on agricultural losses after tephra fall that could be modified for each eruption; where I = rainfall intensity (mm), D = rainfall duration (hours), and c and b are constants unique to each eruption (van Westen & Daag et al. 2005).

7.3.1.1 Empirical data requirements

In order to better quantify the relationship between certain VC and impacts, more empirical testing in a controlled environment is needed. Factors of particular interest, that would be suitable for establishing laboratory or field trials, include the effect of mitigation measures and precipitation levels on agricultural impacts. Previous studies have begun to work towards constraining these relationships (Wilson et al. 2009), however further work is required. Due to difficulties in sourcing enough unweathered, fresh tephra to enable large scale field trials, ideally a series of trial sites for longitudinal impact and recovery studies would be established across a tephra fall depositional area. The physical and chemical tephra properties at these sites would need to be measured and well constrained. These would then undergo various forms of mitigation treatments including: tephra removal, cultivation of tephra into topsoil, and various fertilisation and reseeding regimes. Precise precipitation and weather condition data (such as wind directions and speed which influence aeolian remobilisation) would also need to be recorded at the trial sites. This would require a high level of cooperation with local farmers, agricultural agencies, and possibly municipal authorities.

7.3.2 Accessibility and communication of tools

Ensuring that the post-EIA guidelines, AID, and fragility functions are available to stakeholders, such as other impact assessment and risk scientists, emergency managers, and municipal advisors is vital to encouraging uptake and continuing the development and testing of the proposed tools.

Tools that aid risk assessments, such as the fragility functions proposed in this thesis, are valuable to a range of sectors, including emergency managers, agricultural agencies, and insurance firms. These agencies all require accurate forecasting of impacts from hazards such as tephra fall in order to develop preparedness plans. For the insurance industry ensuring that any estimations are undertaken using a quantitative basis is vital as this allows for numeric estimates of financial impacts. This means that a broad audience needs to understand and be able to use risk tools such as fragility functions. One way to effectively communicate this knowledge is through risk modelling workshops and training sessions, targeted to a specific audience and their experience level, which aim to improve risk literacy (Sinclair et al. 2012).

The proposed agricultural fragility functions are being integrated into the RiskScape software package. This is a risk assessment software package for New Zealand natural hazards being developed by NIWA (National Institute of Water and Atmospheric Research Ltd.) and GNS Science that outputs predicted asset impacts and losses (King & Bell 2006). This will mean that the fragility functions derived here are easily accessible to New Zealand scientists and emergency managers. It is possible that the functions could be used in a GIS to create a similar output, however the incorporation of fragility functions into a specific software interface (such as RiskScape) would significantly aid accessibility and uptake in other countries.

7.3.3 Systems interdependencies

Agricultural systems rely on multiple infrastructure sectors (or ‘lifelines’) including: electricity for milking, shearing, water pumping; communication systems for trading and information access; water supplies for irrigation and livestock; and roading networks for the movement of goods. These lifelines can all be disrupted by tephra impacts. This means that even if agricultural systems are not directly affected by the physical and chemical nature of the tephra fall, subsequent disruption could lead to production losses. For example, a dairy farm may have enough feed that is uncontaminated by tephra to continue feeding cows and maintain milk production, but if electricity outages occur milking and refrigeration equipment will be offline, preventing normal production. Further work on quantifying how disruption to these lifelines will affect agricultural impacts is needed. This will likely require a structured approach that represents the cascading impacts that will occur using various failure modes within a decision tree framework. Investigating the links between critical infrastructures and essential services that are disrupted by a tephra fall event is an emerging research theme for volcanic hazards. By mapping and understanding the relationships between assets and services, points of weakness where any disruption could cause cascading failure can be identified, and plans to increase the system's resilience can be developed (Sword-Daniels et al. 2015). Future work should continue to assess agricultural interdependencies using a holistic approach.

7.4 References

Bonadonna, C., Connor, C. B., Houghton, B. F., Connor, L., Byrne, M., Laing, A., & Hincks, T. K. (2005). Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at Tarawera, New Zealand. Journal of Geophysical Research, 110, 1–21. http://doi.org/10.1029/2003JB002896

Hurst, A. W. (1994). Estimating Fallout ASHFALL – A Computer Program for Estimating Volcanic Ash Fallout Report and Users Guide. Institute of Geological & Nuclear Sciences science report 94/23.

Jenkins, S. F., Wilson, T. M., Magill, C. R., Miller, V., & Stewart, C. (2014). Volcanic ash fall hazard and risk: Technical background paper for the UN-ISDR Global Assessment Report on Disaster Risk Reduction 2015. Retrieved from http://muse.jhu.edu/content/crossref/journals/mln/v120/120.3contributors.html

King, A. B., & Bell, R. (2006). Riskscape New Zealand - A Multihazard Loss Modelling Tool. 2006 NZSEE Conference, Napier, 10-12 March, proceedings (30), 9.

Mercado, R. A., Betram, J., Lacsamana, T., & Pineda, G. L. (1996). Socioeconomic impacts of the Mount Pinatubo eruption. In C. G. Newhall & R. S. Punongbayan (Eds.), Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines. Quezon City: University of Washington Press.

Sinclair, H., Hudson-Doyle, E., Johnston, D. M., & Paton, D. (2012). Assessing emergency management training and exercises. Disaster Prevention and Management, 21(4), 507–521. http://doi.org/10.1108/09653561211256198

UNISDR. (2015). Sendai Framework for Disaster Risk Reduction 2015 - 2030. http://www.wcdrr.org/preparatory/post2015-08-06

Sword-Daniels, V. L., Rossetto, T., Wilson, T. M., & Sargeant, S. (2015). Interdependence and dynamics of essential services in an extensive risk context: a case study in Montserrat, West Indies. Natural Hazards and Earth System Science, 15(5), 947–961. http://doi.org/10.5194/nhess-15-947-2015

Van Westen, C. J., & Daag, a. S. (2005). Analysing the relation between rainfall characteristics and lahar activity at Mount Pinatubo, Philippines. Earth Surface Processes and Landforms, 30(13), 1663–1674. http://doi.org/10.1002/esp.1225

Wilson, G., Wilson, T. M., Deligne, N. I., & Cole, J. W. (2014). Volcanic hazard impacts to critical infrastructure: A review. Journal of Volcanology and Geothermal Research, 286, 148–182. http://doi.org/10.1016/j.jvolgeores.2014.08.030

Wilson, T. M., Cole, J. W., Stewart, C., Cronin, S. J., & Johnston, D. M. (2011). Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. Bulletin of Volcanology, 73, 223–239. http://doi.org/10.1007/s00445-010-0396-1

Wilson, T., Cronin, S., Cole, J., & Johnston, D. (2009). Impacts and rehabilitation of pasture following volcanic ashfall. In Vulnerability of pastoral farming systems to volcanic ashfall hazards (pp. 71–126). University of Canterbury, PhD Thesis.

Wilson, T., & Kaye, G. (2007). Agricultural fragility estimates for volcanic ash fall hazards. GNS Science Report 2007/37.

Appendix A

Supplementary material for availability of ash leachates from the 2011 Cordón Caulle eruption: implications for agricultural systems

Table A.1: Summary of previous agricultural impact case studies.

Volcano	Year	Local agriculture	Physical Impacts	Chemical Impacts	Losses	Reference
Merapi, Indonesia	2006	Rice, tobacco, corn, maize, corn, tomatoes; cows, sheep, goats, chickens for domestic consumption.	Crops smothered by ashfalls, particularly those >35 mm. Tobacco, tomatoes, peppers and corn were vulnerable to stems snapping at >30 mm depth.	Acid burns on plants even when ash thickness as low as 2mm. Chemical impacts on livestock not established (no autopsies).	Chilli pepper, tobacco, tomatoes and corn losses up to 80-100%. Losses lower for crops such as potatoes, onions and cabbages (up to 30%). Cattle weight loss due to contamination of feed led to their prices dropping by up to 75%. Autopsies of the few animals that died were not undertaken.	Wilson et al. 2007
Tungurahua, Ecuador	1999-present	Maize, beans, potatoes, citrus fruits, bananas; chickens and cattle for dairying.	Tooth abrasion, starvation and stomach blockages in cattle. Issues with hot ash burning crops in proximal areas.	Chemical burns to foliage caused plant deaths. Citrus trees burnt in 1999 still small and unhealthy in 2004. 6-8 years soil fertility recovery predicted.	Livestock sold off at less than half price, causing some bank closures. High calf mortality rate. In areas with >200 mm ash 100% of crops died.	Leonard et al. 2005
Mt. Ruapehu, New Zealand	1995-1996	Mostly sheep and cattle for dairying, some horticulture.	Tooth abrasion in cattle. Some vegetation breaking due to tephra loading.	30-1500 kg/ha of sulphur added to >25,000 km^2 of land. Soluble (in water) fluoride levels were around 24-28 mg/kg of tephra.	2000 sheep died 80km NE of the vent (2.5% of sheep in the area) and 3 dairy cows also died, due to suspected fluorosis. These deaths were likely caused by a combination of fluorosis and their existing poor condition. Some sulphur accumulation, particularly in brassica approached toxic levels.	Cronin et al. 1998; Cronin et al. 1997; Cronin et al. 2003; Johnston et al. 2000
Hudson, Chile	1991	Livestock farming for meat and wool, some horticulture in irrigated areas.	Up to 2000 mm of tephra fall. Stomach blockages causing injury and eye irritation in animals. Tephra accumulating in fleeces until sheep could no longer stand up. Remobilisation of ash caused continued problems.	Some reports of acid damage to fruit tree leaves. Lack of pre-eruption data di not allow for quantifying soil chemistry changes. Showed some evidence of limited fertilisation of sulphur.	Approximately 1 million sheep and thousands of cows died due to tephra covering feed. Farm abandonments occurred in the Ibanez Valley (800-2000 mm ash) and the steppe region (up to 75 mm ash).	Inbar et al. 1995; Wilson et al. 2009; Wilson et al. 2011a; Wilson et al. 2011b; Wilson et al. 2012

Volcano	Year	Local agriculture	Physical Impacts	Chemical Impacts	Losses	Reference
Pinatubo, Phillipines	1991	Rice, vegetables, sheep, cattle and poultry farming.	Up to 30 cm of tephra was deposited on the flanks of the volcano that was used for rice and vegetable farming. Crops were smothered. Farmers' houses and shed roofs were collapsed by the weight of the wet ash causing human and animal casualties.	Intense rainfall at the time meant that the tephra was quickly leached. No chemical issues were reported.	96,200 ha of agricultural land covered by ashfall causing US$36.2 million in agricultural damage (including lahars and remobilised tephra).	Mercado et al. 1996
Mt. St. Helens, USA	1980	Fruit trees, hay, potatoes, cereals, legumes.	Issues with photosynthesis in crops where leaves covered with ash. Plant breakages due to loading common. No issues with stomach blockages in livestock. Acted as mulch in some places, lead to good wheat crop.	Salt damage on fruit tree leaves. No toxicity issues in plants or animals observed. Small amount of sulphur added to soil.	US$15 million lost in apple production due to slowed growth. Favourable growth conditions after the eruption means that some crop losses may be masked.	Antos & Zobel 1985; Cook et al. 1981; Dahlgren et al. 1999; Dale et al. 2005; Lyons 1986
Hekla, Iceland	1970	Mostly sheep farming with some crops.	Up to 200 mm of tephra deposited proximal to vent. Chemical issues were more important due to small amount of ash needed to cause lethal fluorosis.	Only 1mm of tephra was shown to cause fluoride toxicity and deaths in sheep. Grass contained 4300 ppm fluoride. This dropped rapidly in the weeks after the eruption.	Thousands of sheep deaths due to acute fluorosis. Contamination of feed meant that large amounts had to be discarded as even small amounts of ash caused animal health issues.	Thorarinsson & Sigvaldason 1971
Paricutin, Mexico	1943-1956	Cattle, horses and some sheep and goats. Small amount of food crops.	All plant life within a 5km radius of the cone died due to smothering by 150-200 mm of tephra. Animals showed some respiratory stress.	Deposits that were able to be cultivated into the topsoil provided some fertilisation.	Area within 10km of vent mostly abandoned after manual tephra removal proved too difficult. Cultivation of deposit into soil successful at <150mm thickness. Approximately 4000 animals died.	Eggler 1963; Rees 1993; Rejmanek et al. 1982

Table A.2: Summary of ash and soil samples collected.

ID	Lat.	Long.	Dist. to Vent (km)	Date Collected	Notes
			2011 Ash Samples		
13_140611	-40.76	-71.65	45	14/06/11	Dry, fresh. Suburban area.
1	-40.90	-71.47	70	5/06/11	Dry, fresh. Forestry land.
040611-6	-41.13	-71.40	75	4/06/11	Dry, fresh. Suburban area.
060611-3	-40.90	-71.49	80	6/06/11	Dry, fresh. Adjacent to Lake Nahuel Huapi.
060611-6	-40.79	-71.14	90	6/06/11	Dry, fresh. Steppe-temperate area transition. Road side location.
080611-3	-41.07	-70.34	225	8/06/11	Slightly damp. Grazing lowland melline.
290611-076	-41.34	-69.67	225	26/06/11	Dry, fresh. Grazing lowland melline.
170611	-41.32	-49.51	235	17/06/11	Dry, fresh. Suburban area.
			2012 Ash Samples		
43	-40.85	-71.52	60	11/03/12	In situ. Forestry land.
41	-40.92	-71.44	70	11/03/12	In situ. Pastoral land.
58	-41.00	-71.34	80	13/03/12	In situ. Pastoral land.
27	-41.11	-70.77	130	6/03/12	In situ. Grazing lowland melline.
25	-41.04	-70.47	150	6/03/12	In situ. Grazing lowland melline.
23	-41.06	-70.33	160	6/03/12	In situ. Grazing lowland melline.
21	-41.07	-70.21	170	6/03/12	Epiclastic. Grazing lowland melline.
20	-41.27	-70.03	190	6/03/12	Epiclastic. Grazing lowland melline.
17	-41.34	-69.70	220	6/03/12	Epiclastic. Suburban area.
13	-41.28	-69.46	235	4/03/12	Epiclastic. Adjacent to Lake Carrilaufqen.
			2012 Soil Samples		
11	-40.68	-71.98	15	4/03/12	Wet, silty soil with anerobic smell, dark brown.
59	-40.72	-71.80	30	13/03/12	Silty loam texture with some clays, reddish brown.
60	-40.71	-71.78	30	13/03/12	Wet, silty soil with anerobic smell, dark brown.
41	-40.92	-71.44	70	11/03/12	Silty loam with some sand, medium brown.
40	-41.00	-71.34	80	11/03/12	Silty loam with some sand, medium brown.
28	-41.04	-71.06	100	6/03/12	Humid loam, dark brown.
27	-41.11	-70.77	130	6/03/12	Humid loam with silt, medium brown.
25	-41.04	-70.47	150	6/03/12	Silty humid loam with some sand, dark brown.
21	-41.07	-70.21	170	6/03/12	Silty humid loam with some sand, medium to dark brown.
20	-41.2	-70.0	190	6/03/12	Silty loam, light brown.
17	-41.3	-69.7	220	4/03/12	Silty loam, light brown.

Table A.3: Spearman's rank correlation coefficient values for A) 2011 1:20 leachate concentrations; and B) 2011 total ash digest concentrations; C) 2012 1:20 water leachable concentrations; and D) 2012 total ash digest concentrations, each correlated with distance from vent and loading.

A) 2011 ash samples - water leachates[1]

	n	Distance to Vent (km)	Significance[2]	Loading (kg/m^2)	Significance	Grain Size (um)	Significance
Ca	8	0.299	Not significant	-0.111	Not significant	0.048	Not significant
Mg	8	-0.029	Not significant	0.309	Not significant	-0.108	Not significant
Na	8	-0.120	Not significant	0.086	Not significant	-0.643	Not significant
Cl	8	0.180	Not significant	-0.371	Not significant	0.071	Not significant
F	8	0.361	Not significant	-0.093	Not significant	-0.671	Very significant

B) 2012 ash samples - water leachates

	n[3]	Distance to Vent (km)	Significance	Loading (kg/m^2)	Significance	Grain Size (um)	Significance
Ca	9	0.812	Very significant	-0.322	Not significant	-0.486	Not significant
Mg	9	0.200	Not significant	-0.200	Not significant	0.229	Not significant
Na	9	0.750	Significant	-0.069	Not significant	-0.067	Not significant
Cl	9	0.771	Significant	-0.265	Not significant	0.416	Not significant
F	9	0.933	Highly significant	-0.156	Not significant	-0.432	Not significant

C) 2011 ash samples - digests

	n	Distance to Vent (km)	Significance	Loading (kg/m^2)	Significance	Grain Size (um)	Significance
Ca	8	0.012	Not significant	0.124	Not significant	0.810	Very significant
Mg	8	0.012	Not significant	0.124	Not significant	0.810	Very significant
Na	8	0.359	Not significant	-0.222	Not significant	0.190	Not significant
K	8	0.024	Not significant	0.173	Not significant	0.571	Not significant
Al	8	-0.611	Significant	0.704	Significant	0.262	Not significant
As	8	-0.144	Not significant	0.284	Not significant	0.476	Not significant
Co	8	-0.252	Not significant	0.235	Not significant	0.810	Very significant
Cu	8	-0.180	Not significant	0.012	Not significant	0.810	Very significant
Fe	8	-0.355	Not significant	-0.298	Not significant	0.419	Not significant
Mn	8	-0.192	Not significant	0.185	Not significant	0.667	Very significant
Ni	8	0.503	Not significant	-0.334	Not significant	0.357	Not significant
Pb	8	0.467	Not significant	-0.334	Not significant	0.095	Not significant
Zn	8	-0.491	Not significant	0.296	Not significant	0.595	Not significant

D) 2012 ash samples - digests

	n	Distance to Vent (km)	Significance	Loading (kg/m^2)	Significance	Grain Size (um)	Significance
Ca	9	-0.300	Not significant	0.364	Not significant	0.225	Not significant
Mg	9	-0.617	Significant	0.234	Not significant	0.139	Not significant
Na	9	-0.017	Not significant	-0.572	Significant	-0.491	Significant
K	9	0.083	Not significant	-0.355	Not significant	-0.418	Not significant
Al	9	-0.350	Not significant	0.286	Not significant	0.212	Not significant
As	9	-0.317	Not significant	-0.095	Not significant	0.455	Not significant
Co	9	-0.333	Not significant	-0.451	Not significant	-0.103	Not significant
Cu	9	-0.783	Very significant	0.165	Not significant	0.285	Not significant
Fe	9	-0.317	Not significant	0.147	Not significant	0.176	Not significant
Mn	9	-0.343	Not significant	0.148	Not significant	0.055	Not significant
Ni	9	-0.667	Significant	0.433	Not significant	0.467	Significant
Pb	9	-0.731	Very significant	0.158	Not significant	0.498	Significant
Zn	9	-0.417	Not significant	-0.286	Not significant	0.224	Not significant

1 Limited number of elements calculated due to a high number being below detection limits for the water leachate datasets.
2 Significance criteria adopted here are: $p<0.001$ highly significant; $0.001<p<0.01$ very significant; $0.01<p<0.05$ significant; $p>0.05$ not significant.
3 Site suspected of fertiliser contaminantion omitted (sample 21).

Table A.4: Testing for differences (using t test) between water extractable element[1] concentrations of the elements listed.

	All data p-value[2]	Significance[3]	Outlier removed p-value	Significance
Ca	0.16	Not significant	0.04	Significant
Mg	0.31	Not significant	0.1	Not significant
Na	0.003	Very significant	0.0005	Highly significant
SO_4	0.46	Not significant	0.032	Significant
Cl	0.026	Significant	0.0015	Very significant
F	0.009	Very significant	0.0094	Very significant

1. Comparisons for other elements were not done, as high proportions of data were below detection limits.
2. Comparisons are for one tailed t test comparing two samples with unequal variances.
3. Significance criteria adopted here are: $p<0.001$ highly significant; $0.001<p<0.01$ very significant; $0.01<p<0.05$ significant; $p>0.05$ not significant.
4. No difference as no outlier in F data set

Table A.5: Surface water properties and contaminant concentrations of water samples taken in 2011.

Site	Sampling Date	Distance from vent (km)	pH	Conductivity (µS/cm)	Cl (mg/L)	F (mg/L)	SO4 (mg/L)	Total Al (ug/L)	Total As (ug/L)	Total Cu (ug/L)	Total Fe (ug/L)	Total Mn (ug/L)	Total Pb (ug/L)
Rio Pireco	22/06/11	35	6.83	58	11.3	0.49	0.9	370	<1	1.05	260	21	0.32
Arroyo Totoral	22/06/11	36	6.7	74	16.6	0.91	1.9	1010	<1	2.8	760	31	0.73
Lago Espejo Chico	23/06/11	37	6.7	22	1.4	0.25	1.5	19.8	<1	0.61	<20	3.8	0.3
Arroyo Espejo Chico	23/06/11	37	7.3	39	1.2	0.2	2.2	34	<1	<0.5	23	0.55	0.2
Rio Ruca Malen	14/06/11	38	7.1	20	1.1	0.13	1.6	14.7	<1	<0.5	<20	0.71	0.1
Rio Pichitraful	23/06/11	44	7.4	51	2.3	0.12	3.3	60	<0.1	<0.5	61	3.9	0.4
Arroyo Las Piedritas	8/06/11	50	6.7	110	26	1.57	69	18.9	10.2	1.33	<20	4	0.2
	14/06/11		7	50	8	0.66	2.8	21	<1	0.65	<20	0.99	0.22
Arroyo unnamed	6/06/11	57			4.2	0.32	2.6	250	2.6	1.52	250	9.3	0.33
Arroyo la Estacada	6/06/11	62			3.3	0.35	0.5	104	<1	0.64	96	3.8	<0.1
	8/06/11		6.4	127	21	1.37	4.6	570	<1	2.1	310	15.1	0.51
	14/06/11		7.1	41	7.4	0.64	<0.5	35	<1	0.9	24	1.02	0.62
Arroyo Ragintuco	6/06/11	64			2.8	0.33	0.9	105	<1	0.69	100	4	<0.1
Arroyo Huemul	6/06/11	70			2.4	0.25	1.7	189	<1	0.66	164	4.4	<0.1
	14/06/11		7.4	53	7.6	0.7	1.2	35	<1	0.81	<20	0.59	0.46
Arroyo Cullin Manzano	14/06/11	88	7.55	71	9.4	1.08	1.6	58	<1	0.82	39	1.3	0.3
Rio Nirihuau	30/06/11	102	7.76	66	1.1	0.07	2.9	8.4	1.3	0.79	24	0.67	0.18
Arroyo Comallo	8/06/11	164	8	633	28	1.35	1.2	43	<1	0.87	<20	5.6	0.33
Rio Quetrequile	29/06/11	262	8.1	657	24	1.2	48	15	4.3	1.2	42	1.9	0.18

Table A.6: Comparison of surface water properties taken from similar locations in 2011 and 2012.

Site		**Arroyo Huemul**				**Arroyo La Estacada**					**Arroyo Las Piedritas**			**Arroyo Totoral**	
Climate Zone		Temperate				Temperate					Temperate			Temperate	
Sampling Date		6/06/11	14/06/11	1/03/12	11/03/12	6/06/11	8/06/11	14/06/11	1/03/12	11/03/12	8/06/11	14/06/11	14/03/12	22/06/11	14/03/12
Distance from vent (km)		70	70	70	70	62	62	62	62	62	50	50	50	36	36
Weather conditions				Rainy	Dry				Rainy	Dry			Dry		Dry
pH			7.4	7.3	7.4		6.4	7.1	7.2	7.1	6.7	7	7.1	6.7	6.8
Conductivity (µS/cm)			53	62	61		127	41	56	55	110	50	76	74	75
H+			4.07E-08	5.01E-08	3.98E-08		3.72E-07	8.71E-08	6.31E-08	7.94E-08	1.95E-07	1.00E-07	7.94E-08	2.14E-07	1.58E-07
Cl (mg/L)		2.4	7.6	6.6	5.6	3.3	21	7.4	7.2	5.9	26	8	5.6	16.6	9.2
F (mg/L)		0.25	0.7	0.11	0.09	0.35	1.37	0.64	0.11	0.08	1.57	0.66	0.08	0.91	0.33
SO4 (mg/L)		1.7	1.2	1.6	1.5	0.5	4.6	<0.5	<0.5	<0.5	69	2.8	4.3	1.9	1.8
Al (ug/L)	**Dissolved**			11	4				8	5			5		6
	Total	189	35	580	51	104	570	35	450	26	18.9	21	123	1010	183
As (ug/L)	**Dissolved**			<1	<1				<1	<1			<1		<1
	Total	<1	<1	<1	<1	<1	<1	<1	<1	<1	10.2	<1	<1	<1	<1
Cu (ug/L)	**Dissolved**			<0.5	<0.5				<0.5	<0.5			<0.5		0.6
	Total	0.66	0.81	1.15	<0.5	0.64	2.1	0.9	1.4	<0.5	1.33	0.65	0.85	2.8	1.43
Fe (ug/L)	**Dissolved**			<20	<20				<20	<20			60		140
	Total	164	<20	430	40	96	310	24	420	34	<20	<20	230	760	720
Mn (ug/L)	**Dissolved**			<0.5	0.8				<0.5	<0.5			<0.5		0.6
	Total	4.4	0.59	10.4	4.1	3.8	15.1	1.02	13.6	1.91	4	0.99	14.7	31	144
Pb (ug/L)	**Dissolved**			<0.1	<0.1				<0.1	<0.1			<0.1		<0.1
	Total	<0.1	0.46	0.17	<0.1	<0.1	0.51	0.62	0.19	<0.1	0.2	0.22	0.13	0.73	0.13

Appendix B

Supplementary information for agricultural impact assessment and management after three widespread tephra falls in Patagonia, South America

Table B.1: Total area covered by initial tephra fall and the percentage land-use types affected for A) CC-VC eruption; B) Chaiten eruption: C) Hudson eruption.

A) Tephra Thickness (mm)	1-10		>10-25		>25-50		>50-100		>100-150		>150-300		>300	
Land-use within tephra isopachs (FAO 2008)	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
No data	633	0	0	0	0	0	0	0	0	0	0	0	0	0
Forest - virgin	2094	1	730	2	243	2	73	3	0	0	0	0	0	0
Forest - protected	730	<0.1	219	1	487	4	657	30	560	49	219	45	365	83
Forest - with agricultural activities	1826	1	365	1	414	3	49	2	0	0	0	0	0	0
Forest - with moderate or higher livestock density	1680	1	390	1	0	0	0	0	0	0	0	0	0	0
Grasslands - unmanaged	390	<0.1	49	<0.1	0	0	0	0	0	0	0	0	0	0
Grasslands - protected	97	<0.1	49	<0.1	341	3	219	10	49	4	49	10	73	17
Grasslands - low livestock density	2508	1	195	<0.1	292	2	49	2	0	0	0	0	0	0
Grasslands - moderate livestock density	1169	<0.1	170	<0.1	0	0	0	0	0	0	0	0	0	0
Grasslands - high livestock density	365	<0.1	0	0	0	0	0	0	0	0	0	0	0	0
Shrubs - unmanaged	511	<0.1	49	<0.1	49	0	0	0	0	0	0	0	0	0
Shrubs - protected	4334	1	24	<0.1	292	2	73	3	268	23	49	10	0	0
Shrubs - low livestock density	77578	25	4334	10	1534	11	195	9	0	0	0	0	0	0
Shrubs - moderate livestock density	45729	15	1193	3	170	1	0	0	0	0	0	0	0	0
Shrubs - high livestock density	4456	1	0	0	0	0	0	0	0	0	0	0	0	0
Rainfed crops	170	<0.1	195	<0.1	97	1	0	0	0	0	0	0	0	0
Crops and mod. intensive livestock density	584	<0.1	0	0	0	0	0	0	0	0	0	0	0	0
Crops and high livestock density	146	<0.1	0	0	0	0	0	0	0	0	0	0	0	0
Crops, large-scale irrig., mod. or higher livestock dens.	243	<0.1	0	0	0	0	0	0	0	0	0	0	0	0
Agriculture - large scale Irrigation	755	<0.1	0	0	0	0	0	0	0	0	0	0	0	0
Agriculture - protected	0	0	0	0	146	1	24	1	24	2	0	0	0	0
Urban land	3409	1	73	<0.1	97	1	24	1	0	0	97	20	0	0
Wetlands - unmanaged	1534	<0.1	414	1	24	<0.1	24	1	0	0	0	0	0	0
Sparsely vegetated areas - unmanaged	414	<0.1	730	2	268	2	0	0	0	0	0	0	0	0
Sparsely vegetated areas - protected	11810	4	438	1	317	2	195	9	97	9	0	0	0	0
Sparsely vegetated areas - with low livestock density	63552	20	25713	60	7646	57	487	22	0	0	0	0	0	0
Sparsely vegetated areas - mod. or high livestock dens.	79794	26	6794	16	536	4	0	0	0	0	0	0	0	0
Bare areas - unmanaged	49	<0.1	97	<0.1	0	0	0	0	0	0	0	0	0	0
Bare areas - protected	97	<0.1	49	<0.1	97	1	0	0	0	0	0	0	0	0
Bare areas - with low livestock density	1461	<0.1	195	<0.1	0	0	0	0	0	0	0	0	0	0
Bare areas - with mod. livestock density	487	<0.1	0	0	0	0	0	0	0	0	0	0	0	0
Water	2021	1	170	<0.1	365	3	122	6	146	13	73	15	0	0
Total Area (km^2)	310628		42636		13417		2191		1144		487		438	

B) Tephra Thickness (mm)	1-2		2-10		10-30		30-100		>100	
Land-use within tephra isopachs (FAO 2008)	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
No data	146	1	24	<0.1	73	1	0	0	0	0
Forest - virgin	730	5	974	6	925	13	0	0	0	0
Forest - protected	97	1	536	3	755	11	195	10	0	0
Forest - with agricultural activities	487	4	1071	6	1193	17	901	47	97	67
Forest - with moderate or higher livestock density	438	3	730	4	804	11	0	0	0	0
Grasslands - unmanaged	219	2	268	2	122	2	219	12	24	17
Grasslands - protected	49	<0.1	73	<0.1	317	5	73	4	0	0
Grasslands - low livestock density	73	1	97	1	97	1	97	5	0	0
Grasslands - moderate livestock density	122	1	243	1	73	1	49	3	0	0
Shrubs - unmanaged	97	1	49	<0.1	195	3	0	0	0	0
Shrubs - protected	0	0	146	1	97	1	0	0	0	0
Shrubs - low livestock density	560	4	633	4	122	2	0	0	0	0
Shrubs - moderate livestock density	24	<0.1	1144	7	97	1	0	0	0	0
Shrubs - high livestock density	0	0	0	0	49	1	0	0	0	0
Crops and mod. intensive livestock density	97	1	146	1	0	0	97	5	0	0
Crops and high livestock density	0	0	0	0	97	1	0	0	0	0
Agriculture - protected	0	0	0	0	49	1	0	0	0	0
Urban land	0	0	0	0	97	1	0	0	0	0
Wetlands - unmanaged	219	2	0	0	24	<0.1	0	0	0	0
Sparsely vegetated areas - unmanaged	268	2	97	1	195	3	0	0	0	0
Sparsely vegetated areas - protected	0	0	0	0	97	1	0	0	0	0
Sparsely vegetated areas - with low livestock density	7768	56	3214	19	219	3	49	3	0	0
Sparsely vegetated areas - mod.or high livestock dens.	2167	16	6940	42	1096	16	0	0	0	0
Bare areas - unmanaged	0	0	0	0	49	1	0	0	0	0
Bare areas - with low livestock density	146	1	24	<0.1	49	1	73	4	0	0
Bare areas - with mod. livestock density	49	<0.1	24	<0.1	73	1	73	4	0	0
Open Water - protected	0	0	0	0	0	0	49	3	0	0
Open Water - inland Fisheries	0	0	73	<0.1	49	1	24	1	24	17
Total Area (km^2)	13758		16509		7013		1899		146	

C) Tephra Thickness (mm)	1-10		10-20		20-50		50-100		100-300		300-1000		>1000	
Land-use within tephra isopachs (FAO 2008)	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
No data	2045	5	1437	6	1096	5	97	0	0	0	0	0	0	0
Forest - virgin	1315	3	755	3	365	2	560	2	146	14	219	23	0	0
Forest - protected	268	1	219	1	97	0	24	0	0	0	0	0	0	0
Forest - with agricultural activities	682	2	195	1	97	0	146	1	24	2	0	0	0	0
Forest - with moderate or higher livestock density	536	1	97	0	268	1	146	1	73	7	24	3	0	0
Grasslands - unmanaged	390	1	414	2	146	1	73	0	146	14	24	3	24	7
Grasslands - protected	268	1	390	2	49	0	97	0	0	0	0	0	0	0
Grasslands - low livestock density	1315	3	536	2	536	2	365	2	170	16	122	13	97	29
Grasslands - moderate livestock density	97	0	49	0	73	0	122	1	24	2	122	13	0	0
Shrubs - unmanaged	122	0	49	0	0	0	49	0	0	0	0	0	0	0
Shrubs - protected	0	0	49	0	49	0	146	1	0	0	0	0	0	0
Shrubs - low livestock density	1997	5	1461	6	1802	8	2289	10	73	7	0	0	0	0
Shrubs - moderate livestock density	49	0	0	0	24	0	24	0	0	0	97	10	0	0
Rainfed crops (Subsistence/Commercial)	487	1	24	0	97	0	146	1	0	0	0	0	0	0
Crops and mod. intensive livestock density	24	0	0	0	0	0	0	0	0	0	0	0	0	0
Agriculture - protected	122	0	24	0	24	0	49	0	0	0	0	0	0	0
Urban land	170	0	24	0	0	0	0	0	0	0	0	0	0	0
Wetlands - unmanaged	633	2	633	2	706	3	365	2	24	2	73	8	0	0
Sparsely vegetated areas - unmanaged	682	2	268	1	657	3	195	1	49	5	0	0	0	0
Sparsely vegetated areas - protected	97	0	170	1	438	2	317	1	0	0	0	0	0	0
Sparsely vegetated areas - with low livestock density	28367	67	18092	70	16022	68	16363	72	73	7	97	10	24	7
Sparsely vegetated areas - mod. or high livestock dens.	292	1	24	0	73	0	341	1	49	5	49	5	49	14
Bare areas - unmanaged	73	0	0	0	0	0	49	0	24	2	0	0	49	14
Bare areas - protected	0	0	0	0	49	0	0	0	0	0	0	0	0	0
Bare areas - with low livestock density	560	1	317	1	292	1	195	1	97	9	49	5	0	0
Open Water - unmanaged	195	0	49	0	49	0	24	0	0	0	0	0	0	0
Open Water - protected	219	1	243	1	24	0	0	0	0	0	0	0	0	0
Open Water - inland Fisheries	1120	3	414	2	487	2	657	3	97	9	73	8	97	29
Total Area (Sq. km)	42125		25932		23522		22840		1071		950		341	

Table B.2: Data from farm interviews conducted between 20 January and 8 February 2008 with respect to impacts received after the 1991 Hudson eruption (summarised and expanded from Wilson et al. 2011).

ID	Event	Location	Country	Distance to vent (km)	Rainfall (mm/yr)	Farm Type	Farmer Thickness (mm)	Actual Thickness (mm)	Hectares	Pasture with no tephra cover (%)	Productive land covered with tephra (%)
2	Hudson	Ibanez Valley	Chile	60	1000	Pastoral	1000	500	120	5	95
3	Hudson	Ibanez Valley	Chile	40	1000	Pastoral	1500	1000	170	0	100
4	Hudson	Ibanez Valley	Chile	50	1000	Pastoral	1250	500	100	5	95
5	Hudson	Ibanez Valley	Chile	50	1000	Pastoral	1250	400	220	5	95
6	Hudson	Ibanez Valley	Chile	50	1000	Pastoral	550	100	160	10	90
7	Hudson	Puerto Ibanez	Chile	75	500	Mixed	125	40	150	20	80
8	Hudson	Puerto Ibanez	Chile	85	500	Mixed	175	40	100	20	80
9	Hudson	Puerto Ibanez	Chile	80	500	Pastoral	150	40	800	10	90
10	Hudson	Puerto Ibanez	Chile	90	500	Mixed	225	40	7.5	25	75
11	Hudson	Puerto Ibanez	Chile	90	500	Horticulture	1000	40	1	-	-
12	Hudson	Puerto Ibanez	Chile	95	500	Mixed	200	40	100	20	80
13	Hudson	Chile Chico	Chile	115	295	Lifestyle	350	100	5	10	90
14	Hudson	Chile Chico	Chile	120	295	Lifestyle	300	100	5	10	90
15	Hudson	Chile Chico	Chile	125	295	Horticulture	400	100	350	20	80
16	Hudson	Chile Chico	Chile	125	295	Pastoral	225	100		10	90
17	Hudson	Chile Chico	Chile	125	295	Pastoral	475	100	520	20	80
18	Hudson	Los Antiguos	Argentina	130	250	Horticulture	1000	80	4	-	-
19	Hudson	Los Antiguos	Argentina	130	250	Horticulture	200	80	8	5	95
20	Hudson	Los Antiguos	Argentina	135	250	Lifestyle	160	80	4	-	-
21	Hudson	Los Antiguos	Argentina	130	250	Pastoral	225	80	70	20	80
22	Hudson	Perito Moreno	Argentina	175	200	Pastoral	400	20		25	75
23	Hudson	Cerro Castillo	Chile	80	650	Pastoral	225	70	180000	35	65
24	Hudson	Cerro Castillo	Chile	80	650	Pastoral	80	70	280	25	75
25	Hudson	Cerro Castillo	Chile	75	650	Pastoral	800	100	100	10	90
26	Hudson	Cerro Castillo	Chile	70	650	Pastoral	900	100		10	90
27	Hudson	Cerro Castillo	Chile	65	650	Pastoral	200	100	9	0	100
28	Hudson	Cerro Castillo	Chile	65	650	Pastoral	250	100	50	10	90
29	Hudson	Puerto Ibanez	Chile	80	500	Pastoral	200	40	60	20	80
30	Hudson	Tres Cerros	Argentina	400	250	Pastoral	45	40	20000	20	80
31	Hudson	Puerto San Julian	Argentina	550	220	Pastoral	30	5	33000	20	80

ID	Cows Pre-eruption	Cow Losses	Cow % Loss	Sheep Pre-eruption	Sheep Losses	Sheep % loss	Other Animals Pre-eruption	Other Animals Losses	Other % losses	Overall % Losses	Animals Sold (%)	Animals Evacuated (%)	Pre-eruption stocking rate (animal/ha)	Post-eruption stocking rate (animal/ha)	Production losses (%)
2	24	9	38							38	40		0.20	0.13	-80
3	33	33	100							100			0.19	0.00	-100
4	30	15	50							50		50	0.30	0.15	-80
5	40	20	50	100	100	100				75		25	0.64	0.09	-80
6	2	2	100	300	200	67				84			1.89	0.63	-40
7	100	25	25	200	170	85				65	35	65	2.00	0.70	-40
8	30	5	17							17			0.30	0.25	-60
9	170	170	100							0	100		0.21	0.00	-50
10	80	20	25							25			10.67	8.00	-20
11										NA			-	-	-15
12				300	260	87	150 Goats	150	100	91		15	3.00	0.40	-80
13	4	0	0							0	100		0.80	0.80	0
14				30						0	100		6.00	6.00	-20
15				400		0				0	100		1.14	1.14	-40
16	300		0							0		100			15
17	100	50	50	400	200	50	3 Horses	0	0	50	50		0.96	0.48	-10
18										NA			-	-	5
19				70	70	100				100			8.75	0.00	0
20										NA			-	-	-25
21				30	15	50				50			0.43	0.21	-10
22				370	80	22				22					-15
23				30000	15000	50				50			0.17	0.08	-80
24	50	1	2	400	60	15				14			1.61	1.39	-25
25	5	0	0	60	0	0				0			0.65	0.65	-60
26										100					-65
27	8	8	100							100	100		0.89	0.00	-30
28	20	20	100	50	50	100				100		100	1.40	0.00	-20
29	25	0	0	300	20	7				7		90	5.42	5.08	0
30				12000	11000	92				92			0.60	0.05	-90
31				16000									0.48	0.48	-80

Table B.3: Data from farm interviews conducted between 24 January and 9 February 2009 with respect to impacts received after the 2008 Chaitén eruption.

ID	Event	Location	Country	Distance to vent (km)	Rainfall (mm/yr)	Farm Type	Farmer Thickness (mm)	Actual Thickness (mm)	Hectares	Pasture with no tephra cover (%)	Productive land covered with tephra (%)
4	Cháiten	Pilcaniyeu	Argentina	250	190	Pastoral	10	5	40000	95	5
6	Cháiten	Pilcaniyeu	Argentina	245	190	Pastoral	5	5	2500	80	20
7	Cháiten	Pilcaniyeu	Argentina	240	190	Pastoral	25	5	1100	75	25
19	Cháiten	Esquel	Argentina	110	500	Lifestyle	20	5	10	70	30
21	Cháiten	Futaleufu	Chile	100	1000	Pastoral	50	150	50	80	20
29	Cháiten	Futaleufu	Chile	80	1000	Horticulture	100	150	3	90	10
30	Cháiten	Chaiten	Chile	75	2000	Pastoral	150	150	200	80	20
34	Cháiten	Chaiten	Chile	70	2000	Pastoral	250	300	302	20	80
101	Cháiten	Chaiten	Chile	20	2000	Pastoral	130	300	100	15	85
113	Cháiten	Chaiten	Chile	25	2000	Pastoral	250	300	2000	5	95
119	Cháiten	Chaiten	Chile	35	2000	Pastoral	80	150	79	60	40
125	Cháiten	Lago Epolon	Chile	70	1000	Pastoral	60	150	147	20	80
189	Cháiten	Esquel	Argentina	110	500	Pastoral	10	5	60	90	10

ID	Cows Pre-eruption	Cow Losses	Cow % Loss	Sheep Pre-eruption	Sheep Losses	Sheep % loss	Other Animals Pre-eruption	Other Animals Losses	Other % losses	Overall % Losses	Animals Sold (%)	Animals evacuated (%)	Pre-eruption stocking rate (animal/ha)	Post-eruption stocking rate (animal/ha)	Production Changes (%)
4	600	0	0	30000	0	0				0			0.77	0.77	0
6				3000	300	10				10			1.20	1.08	-10
7				16000	600	4				4			14.55	14.00	-10
19							62 Chickens	0	0	0			-	-	0
21	80	0	0	50	0	0				0	100		2.60	2.60	-40
29	4	0	0							0	75		1.33	1.33	-10
30	30	0	0							0		100	0.15	0.15	-30
34	50	40	80	29	0	0				0	100		0.26	0.13	-60
101	20	20	100	15	15	100				100			0.35	0.00	-80
113	100	100	100	40	40	100				100			0.07	0.00	-100
119	15	0	0	20	2	10				10			0.44	0.42	-15
125	150	90	60							60	40		1.02	0.41	-40
189	150	0	0							0			2.50	2.50	0

Table B.4: Data from farm interviews conducted between 27 February and 16 March 2012 with respect to impacts received after the 2011 Cordón Caulle eruption.

ID	Event	Location	Country	Distance to vent (km)	Rainfall (mm/yr)	Farm Type	Farmer Thickness (mm)	Actual Thickness (mm)	Hectares	Pasture with no tephra cover (%)	Productive land covered with tephra (%)
19	Puyehue-Cordón Caulle	Jacobacci	Argentina	200	160	Pastoral	50	50	4000	25	75
22	Puyehue-Cordón Caulle	Comallo Town	Argentina	170	160	Pastoral	35	40	10	10	90
23	Puyehue-Cordón Caulle	Comallo Valley	Argentina	160	160	Pastoral	70	50	1000	30	70
62	Puyehue-Cordón Caulle	Rio Totoral	Argentina	50	871	National Park	400	350	100	35	65
63	Puyehue-Cordón Caulle	Nahuel Huapi	Argentina	40	871	National Park	300	350	100	35	65

ID	Cows Pre-eruption	Cow Losses	Cow % Loss	Sheep Pre-eruption	Sheep Losses	Sheep % loss	Other Animals Pre-eruption	Other Animals Losses	Other % losses	Overall % Losses	Animals Sold (%)	Pre-eruption stocking rate (animal/ha)	Post-eruption stocking rate (animal/ha)	Production Losses (%)
19	200	35	18	1600	400	25				24		0.45	0.34	-50
22				30	5	17				17		3.00	2.50	-60
23	50	50	100	164	120	73				73		0.21	0.04	-80
62	100	3	3							3		1.00	0.97	-10
63	50	0	0				5 Horses	0	0	0	100	0.50	0.50	-20

Appendix C

Supplementary material for forecasting impacts to agriculture from tephra fall

Table C.1: Review of previous vulnerability and fragility functions developed for volcanic hazards.

Reference	Asset	Hazard	Hazard intensity measure	Impact measure	Curve fitting method	Strengths	Weaknesses
Pomonis et al. 1999	Buildings	Tephra fall	Tephra thickness (mm)	Probability of roof collapse	Linear	Roof type descriptors include specific spacing of rafters as well as material type. Loading capacities experimentally tested.	Only four roof types represented. No volcanic eruption has been experienced by the currrent population, so totally reliant on experimental data.
Spence et al. 2005	Buildings	Tephra fall	Loading (kPa)	Probability of roof collapse	Cumulative lognormal distribution	Uses analytical studies and observed damage.	Relies on only a few case studies (primarily Azores & Pinatubo). Difficulties in gathering consistent empirical information and failure mechanisms for varied constructions.
Wilson & Kaye 2007	Agriculture	Tephra fall	Tephra thickness (mm)	Production loss	Weibull methodology	Divide agriculture into different sectors and incorporate the importance of seasonal variation.	Reliant on expert judgement. Arbitrary seasonal vulnerability coefficients used. Do not take into account different farm intensities or sizes.
Kaye 2007	Stormwater and roading systems	Tephra fall	Tephra thickness (mm)	Damage ratio (cost of damage/cost of replacement)	Linear	First attempt to create fragility functions for New Zealand infrastructure. Using both experimental and observational data.	Some personal judgement by author required. Not developed with a range of infrastructure designs in mind.

Reference	Asset	Hazard	Hazard intensity measure	Impact measure	Curve fitting method	Strengths	Weaknesses
Zuccaro et al. 2008	Buildings	Tephra fall	Loading (kPa)	Probability of buildings within a damage level	Cumulative lognormal distribution	Hybrid data source, combining numerical modelling, experiments, and probability distributions. Monte Carlo simulation of a range of geometrical & mechanical characteristics.	Focuses on the Vesuvius area. Numerous assumptions made in hazard and exposure modelling. Uncertainty greater with some building typologies.
Jenkins & Spence 2009	Buildings	Tephra fall	Loading (kPa)	Exceedance probability of failure	Cumulative lognormal distribution	Utilises both empirical data from post-eruption observations and experimental data.	Generalised building typologies that may not be applicable in all areas. Mainly focussed on six volcanoes so may not work in all scenarios.
Wardman et al. 2012	Electrical networks	Tephra fall	Tephra thickness (mm)	Probability of flashover	Logarithmic function	First to create fragility functions for electrical supplies. Used experimental data and considers both wet & dry	Small number of case studies. Data points do not clearly take logarithmic form.

Reference	Asset	Hazard	Hazard intensity measure	Impact measure	Curve fitting method	Strengths	Weaknesses
Maqsood et al. 2014	Buildings	Tephra fall	Loading (kPa)	Damage index (cost of damage/cost of replacement)	Various - using curve fitting software tool ELoss	Large number of building types and designs included. Expert judgement was undertaken independently of other participants. Attempts to include uncertainty.	Recognises the need for improved post-disaster surveys to gather data, refining the building schema so it can be used across all hazards, and including insurance industry personnel.
Spence et al. 2004	Windows	PDC	Dynamic pressure (kPa)	Probability of window glazing failure	Logarithmic function	Experimental data was used to create curves.	For other building components dynamic pressure thresholds are assigned to damage scale, but not fragility functions were created.
Zuccaro et al. 2008	Buildings	PDC	Dynamic pressure (kPa)	Probability of buildings within a damage level	Linear and cumulative lognormal distribution	Hybrid data source, combining numerical modelling, experiments, and probability distributions. Monte Carlo simulation of a range of geometrical & mechanical characteristics.	Focuses on the Vesuvius area. Numerous assumptions made in hazard and exposure modelling. Uncertainty greater with some building typologies.

Reference	**Asset**	**Hazard**	**Hazard intensity measure**	**Impact measure**	**Curve fitting method**	**Strengths**	**Weaknesses**
Jenkins & Spence 2009	Buildings	PDC	Dynamic pressure (kPa)	Exceedance probability of failure	Cumulative lognormal distribution	Utilises both empirical data from post-eruption observations and experimental data.	Generalised building typologies that may not be applicable in all areas. Mainly focussed on six volcanoes so may not work in all scenarios.
Zuccaro & De Gregorio 2013	Buildings	PDC	Loading (kPa)	Roof collapse probability	Logarithmic function	Expert judgement and analytical modelling of hazard combined with experimental testing carried out in the Vesuvius area.	Acknowledges uncertainty but requires further work to quantify this.
Kaye 2007	Buildings	Ballistics	Block diameter (m)	Damage ratio (cost of damage/cost of replacement)	Linear	Combines analytical modelling of ballistic impact energies with data from previous studies.	Uses EJECT! (Rasa et al. 2006) to model ballistic size and energy, however this was not designed as a predictive model. Input parameters such as density, velocity, and drag had to be estimated.

Appendix D
Impacts of the June 2011 Puyehue-Cordón Caulle volcanic complex eruption on urban infrastructure, agriculture and public health

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